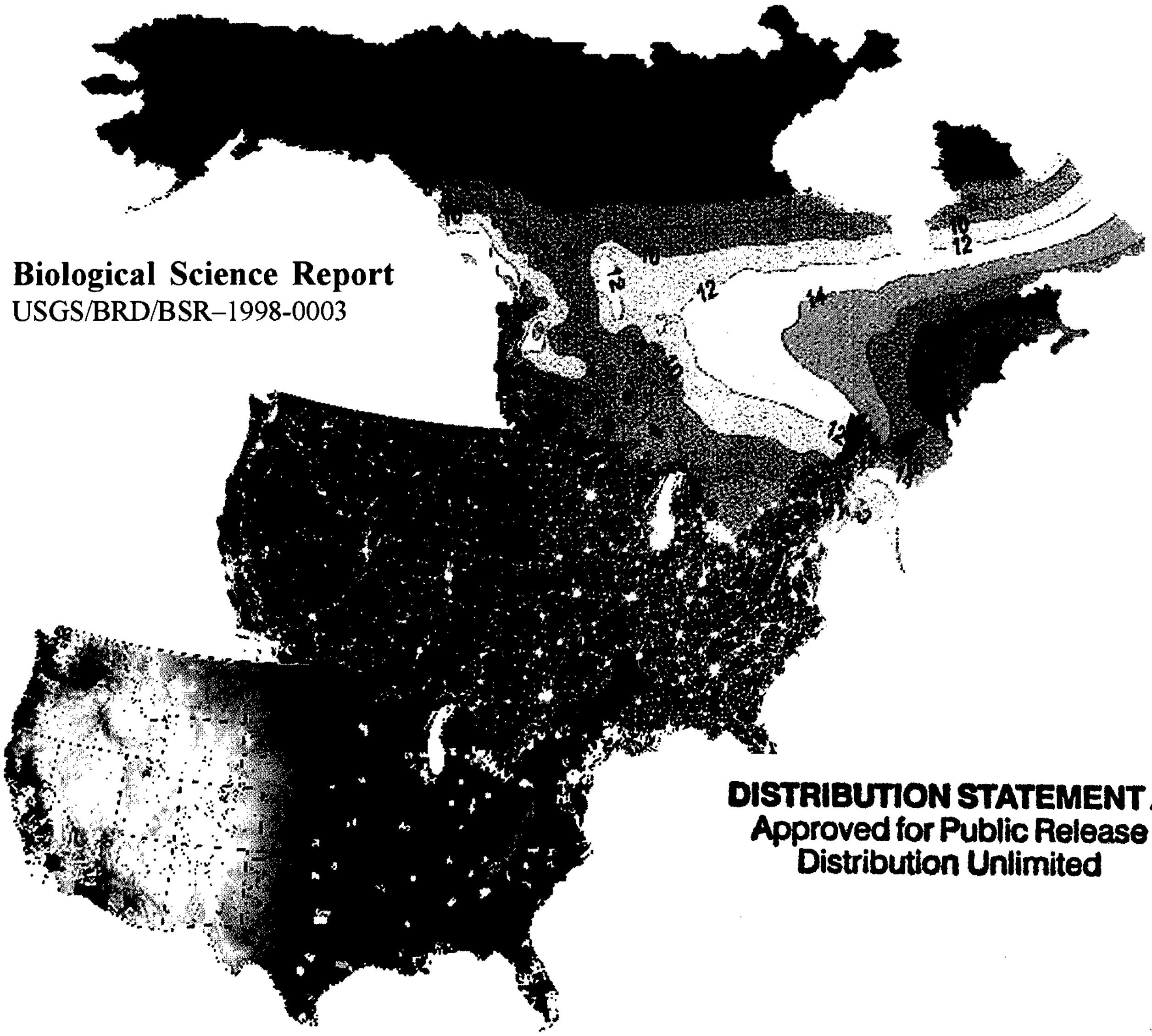
Perspectives on the Land Use History of North America: A Context for Understanding Our Changing Environment



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Perspectives on the Land Use History of North America: A Context for Understanding Our Changing Environment

Biological Science Report
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September 1998

By

Thomas D. Sisk, editor

Production and editorial assistance from Maury Nyquist, Ralph Root, and Susan Stitt, U.S. Geological Survey, Biological Resources Division, and the publication staff of the USGS National Wetlands Research Center.

Abstract: Ecological change is constant and profound, yet it often occurs at temporal and spatial scales that are difficult to measure and interpret. This publication demonstrates how diverse data bases, archived in different formats and at numerous locations, can be brought together to provide an integrated perspective on the relationship between land use and landcover change. The authors provide the historical context for interpreting recent landcover change in several regions of North America and articulate the value of a comprehensive, continental land-use history for guiding environmental policy and management decisions during the coming century and beyond.

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Visit the LUHNA web site at http://www.nbs.gov/luhna/

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Preface

One of the recurring themes of recent environmental literature is the dynamic nature of the Earth. We now accept that concepts of nature as static and unchanging are outmoded and that continuous change characterizes the planet, from its molten interior to the outer atmosphere, including the planet's surface and the ecosystems and biological diversity it supports. Yet while that realization is profound and perhaps long overdue, it immediately poses a host of related questions that are currently very difficult to answer: What types of changes are occurring now? How fast are they occurring? How do these changes compare with those that occurred in the past? And what does it all mean for future environmental quality and the habitability of the planet?

This publication addresses some of these questions for several regions of North America, but more importantly (and more ambitiously), it strives to convey the importance of a historical context for understanding ongoing changes in land cover and land use. It also aims to inspire scientists, educators, and science administrators to contribute to the development of a comprehensive land-use history of North America to guide environmental policy and management decisions during the coming century and beyond.

The efforts that have led to this volume began during the early months of the National Biological Service (NBS), now the Biological Resources Division (BRD) of the U.S. Geological Survey. As the NBS sought to understand and articulate the needs of resource managers to scientists and policy makers, and to chart a course for integrating future biological research efforts, the value of historical land-use and landcover data became clear. In 1995, an initial workshop convened a group of scholars and resource managers working on the issues of land use, land cover, and ecological change. Historians, geographers, ecologists, and sociologists met with policy makers from resource management agencies and nongovernmental institutions to discuss how disparate data sources, archived in different formats and at numerous locations, might be brought together to provide an integrated perspective on land cover and land-use history, from pre-European times to the present.

Following upon the recommendations that emerged from that meeting, NBS initiated the Land Use History of North America program—LUHNA—to guide future efforts to improve understanding of the relationship between historical land use and land cover. As a first step in developing LUHNA, NBS and NASA's Mission to Planet Earth (now the Earth Science Enterprise) jointly sponsored the 10 pilot projects whose results are presented in this volume and a related site on the World Wide Web (http://biology.usgs.gov/luhna). But the work presented in these venues far exceeds what could have been produced solely from the modest support offered by the fledgling LUHNA project. In all cases, the authors drew from ongoing projects and synthesized many years of original research to produce overviews of environmental change from around the continent.

Each chapter was reviewed independently by peer scientists. Editorial work at the National Wetlands Research Center resulted in a presentation that is informative and authoritative, yet accessible to the nonspecialist. Throughout its rather long and punctuated development, the LUHNA project has benefited from the support of visionary leaders within NASA and the Department of the Interior. This publication, however, exists primarily because of the deep commitment of the contributing authors to the goal of creating a comprehensive land-use history for North America.

The work presented here is the beginning of what we hope will become a much larger effort to develop data products and analytical tools that will allow researchers, resource managers, educators, and the general public to explore and analyze the fascinating history of human land use and changes in land cover. We hope that this long-term perspective will provide a context for assessing environmental conditions, interpreting current trends, and making more informed policy and management decisions for the future.

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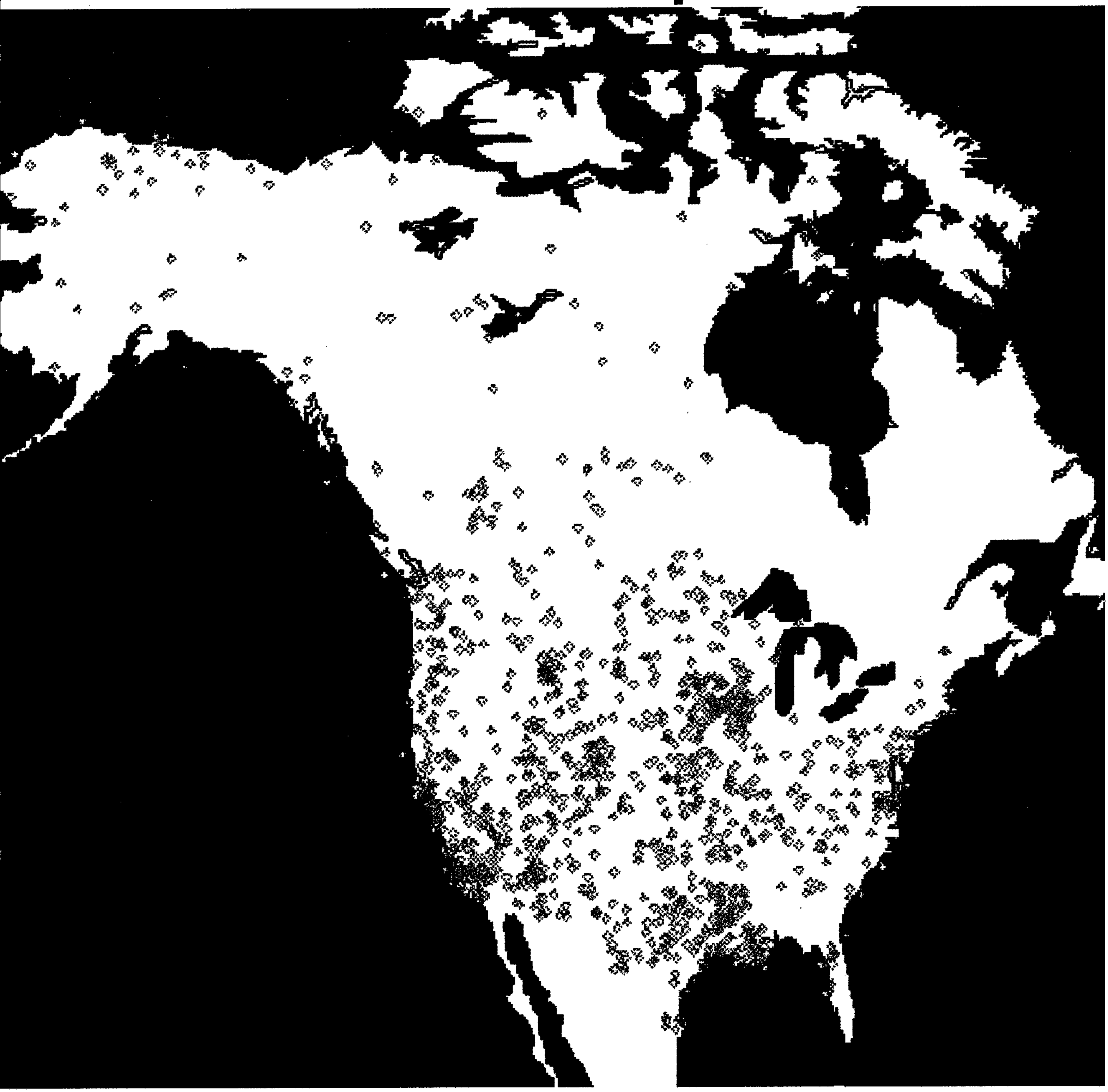
PART 1:
Continental Perspectives



Chapter 1: Toward a Land-Use History of North America: A Context for Understanding Environmental Change

by

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We inhabit a changing planet. Most of us realize that our lives are lived on a scale that is insignificant compared to geological time—continents break up and drift apart, mountains rise and are worn away by the elements, and all of human civilization is dwarfed by the vastness of Earth's history. What many of us do not recognize is that, like the continents and the mountains, the Earth's living ecosystems are undergoing constant changes as well. While typically faster than the movement of continents, ecological change occurs at a pace that can be difficult to detect over the span of a human lifetime. Many areas that were covered with moist forests when humans moved into western North America are now shrub-dominated deserts (Thompson et al. 1993), and large expanses of arid grassland seen by the pioneers during the westward expansion of the United States have given way to shrubs and woodland (Hastings and Turner 1965). More recently, popular portrayals of the Lewis and Clark expedition have shown Americans how dramatically the Great Plains have been changed by settlement and agriculture, while portions of the northern Rockies still resemble the landscapes described by these early explorers at the beginning of the 19th century (Ambrose 1996).

Many changes in the patterns of North American land forms and vegetation—collectively referred to as landcover change—have resulted from or been influenced heavily by human activities. In most places across the continent, our activities have become the dominant driver of environmental change. Yet the extensive and influential role of human activity is often overlooked in the literature, as well as in our perception of our surrounding landscapes. Why? Throughout human history, each new generation has accepted the state of the world that they inherited from their ancestors. Environmental impacts that preceded them were viewed as natural, or at least normal, so changes occurring over several generations often went undetected (Reichman and Pulliam 1996). Even today, as we strive to minimize or reverse many of the obvious environmental impacts that are occurring during our own lifetimes, more gradual changes, even the critically important ones like climate change and the loss of biological diversity, are seldom fully appreciated.

The Importance of Compiling a Land-Use History

A better understanding of the rate and direction of change in the Earth's ecosystems is important for its own sake, but it is also increasingly vital for interpreting current environmental trends and guiding the management of our natural resources. Scientists and resource managers no longer assume that nature exists in a static, unchanging "natural" condition interrupted only by the work of humans. Instead, we view nature as a dynamic system of which humans are a part, recognizing that a variety of forces—ranging from natural disturbances to climatic change, deforestation, and the conversion of native habitats to agriculture—are constantly interacting to determine the pace and direction of change (Pickett and White 1985). This perception of nature has important implications for our understanding of how nature works and our formulation of appropriate responses to emerging environmental problems.

Setting Management Objectives

The perception of ecosystems as dynamic entities, without a single climax or "natural" state, can make the work of land and resource managers more complex. For example, the authorizing legislation for the National Park Service mandates conservation of "natural and historical objects and the wild life therein...unimpaired for the enjoyment of future generations." It is not clear, however, (except in a few cases, such as historic battlefields) whether the "objects" mentioned are those that were present at the time

the first descriptions of the landscape were recorded, at the time the park was created, or during some other unspecified period. Similarly, how can biological resources be preserved "unimpaired" if change is a characteristic of the ecosystem itself? Whether we are concerned with forests or wildlife, wetlands or the oceans, identifying appropriate management objectives has become a challenging task, one that is almost impossible to accomplish without an understanding of the natural rate of change and range of variation within natural systems (National Research Council 1992).

Policy makers, and those who advise them, must ask not only whether environmental change is occurring, but also how it fits into the historical context. Certain changes, such as the sustainable harvest of fish and wildlife populations or well-planned logging practices, may fall within the typical range of variation for the ecosystem and require no mitigating management response. Other trends, such as the filling of wetlands and the rapid liquidation of old growth forests, may have no historical precedent, suggesting that decisive action may be necessary to prevent unacceptable ecosystem degradation. Recognizing the difference between these situations constitutes a critical new challenge for environmental scientists, yet without reliable historical records, the differences may be impossible to distinguish, making it difficult to identify an appropriate course of action. Increasingly, applied ecologists are trying to understand the effects of management alternatives in the context of background rates of change in ecological systems, often referred to as the natural range of variation or NRV. A comprehensive history of changes in land use and land cover could identify this variability, enabling policy makers and resource managers to make more informed decisions as they face increasingly complex choices regarding the use and conservation of the resources entrusted to their care.

Understanding Global Change

Technical advances during the past 25 years have unequivocally shown that the entire Earth is undergoing rapid ecological change, and the most obvious and pronounced change is caused by human land use (Vitousek 1994). Perhaps the most remarkable evidence of such change has emerged from the deployment of Landsat and a host of other satellites and airborne sensors. The images acquired through remote sensing technology give us an unprecedented perspective on current land use, and they allow us to track land-use changes during the latter part of the 20th century. Trends detected during the relatively short period of space-based measurements, however, can be difficult to interpret. While the devastating implications of tropical deforestation and other extreme trends are obvious from recent Landsat images (Skole and Tucker 1993), our understanding of more subtle patterns of landcover change, such as the reforestation of the eastern deciduous forests and the spread of shrubs across the arid Southwest, often require a perspective that reaches back before the space age. Longer timelines can be compiled from historical archives. For example, evidence of early landcover change from photographs, accounts from 18th and 19th century land surveys, and paleoecological evidence from fossil pollen and fire scars can be assembled and analyzed through a multidisciplinary land-use history program. By integrating many sources of historical data and developing the scientific and statistical tools for analyzing change, the land-use history program will increase the value of information obtained from modern remote sensing programs by making it possible to interpret these data in the context of a comprehensive, albeit far less detailed, timeline stretching back before the European settlement of North America and, in many cases, back to the last ice age or earlier.

Uncovering Cause and Effect

A descriptive approach to landcover change will identify historic trends and current conditions, but the prediction of future changes in land cover and their effects requires an improved understanding of the cause-and-effect relationships that link human activities with changes in land use and land cover. Much of the impact that humans have had on the environment can be viewed as a series of unplanned experiments, with particular perturbations generating measurable responses in the form of contractions in the ranges of some species and expansions in the ranges of others. Within the context of these temporal dynamics, species extinctions and the spread of nonnative species may be seen as the extreme cases, where biological elements are lost or introduced.

Many of these "experiments" have been run repeatedly throughout human history. As civilizations have expanded and declined, they have left their marks on landscapes, and environmental scientists are developing ingenious techniques for assembling the data needed to assess the results. By analyzing the relationships between changes in land use and land cover at multiple temporal and spatial scales, it is possible to more confidently distinguish human-induced change from background climatic variation and other natural variability. A better understanding of the cause-and-effect relationships that underlie changes in land cover will lead to better predictive models for land-use planning and improved assessment of the likely outcomes of alternative land-use scenarios.

Increasing Environmental Awareness

Understanding landcover change and adopting a dynamic perspective on North American ecosystems have led many specialists to a deeper understanding of the environment and the place of humans in it. A comprehensive land-use history for North America offers many opportunities for extending this understanding to a broader audience, allowing citizens to explore the complex and often

striking long-term shifts in land use and land cover that characterize the regions where they live.

Part of the reason that many people have difficulty appreciating the importance of environmental change is that our perception of the world is constrained by the scale at which we live our lives. We typically are preoccupied with events that occur over time scales of a few minutes to a few months and spatial scales ranging from our front lawns to a city block or farm field. Ongoing environmental changes, occurring over extensive areas at rates that vary over many orders of magnitude, are often overlooked when examined at these human scales. Graphical presentations of landcover and land-use change over longer time periods and larger areas provide a powerful introduction to the changing face of North America. The subsequent chapters of this publication provide vivid examples of how maps and graphics can reveal striking patterns over different temporal and spatial scales, challenging us to expand and sharpen our perception of environment. Emerging digital technologies offer unlimited opportunities for extending this approach to museum displays, films, on-line productions, and other educational resources.

Science and the Historical Perspective

While the value of a land-use history to the environmental sciences is clear, scientific inquiry often has been divorced from or in conflict with historical narrative. One of the world's most influential ecologists, Robert MacArthur, wrote that "unraveling the history of a phenomenon has always appealed to some people and describing the machinery of the phenomenon to others. In both processes generalizations can be made and tested against new information so both are scientific, but the same person seldom excels at both" (MacArthur 1972, p. 239). More recently, the escalating severity of environmental problems and the difficulties involved in trying to solve them have led an increasing number of scientists to attempt to do both, often with startling insight. Commonly, the scientific objective of understanding the "machinery" or cause-and-effect relationships that drive environmental issues requires an unraveling of historical factors. For example, concerns over increasing concentrations of carbon dioxide in the atmosphere, and the implications this has for climate change, have led scientists to examine air trapped in rock and ice thousands of years ago. Analyses of the "ancient air" have allowed scientists to reconstruct a record of atmospheric CO_2 concentrations reaching back 160,000 years (reviewed in Vitousek 1994). This history has demonstrated that the build-up of CO_2 and other greenhouse gases since the industrial revolution is unprecedented, at least since the last ice age. For many people, this finding suggests that the ever-increasing production of greenhouse gases, with their potential to warm the atmosphere and disrupt climatic patterns, is indeed a serious problem that demands serious attention. Similarly, the reconstruction of fire histories, records of changing climates, and studies of shifts in plant communities give us a deeper perspective on current environmental trends and help us interpret their meaning and importance.

Of course, historical approaches can be misused in scientific inquiry, particularly if we refer to historical information to shore up dubious data, or to "explain away" or downplay controversial scientific observations, or to make observations fit with our previous expectations. Uncritical use of historical arguments has hindered the development of ecological science in the past (Peters 1991), underscoring the need for rigorous, repeatable, and clearly documented approaches to reconstructing the history of land-use and landcover change. Rather than weaving together a historical narrative to "paint a picture" of environmental change, a science-based history of land use will provide a means for placing current conditions and recent trends into a broader temporal context. Compilation of historical trends will allow us to begin to associate cause and effect, exploring the relationship between human activities and environmental change. It also will help us identify the most important questions for future scientific research.

Toward a Comprehensive Land-Use History of North America

Compiling a history of land use and land cover is a large undertaking, one already begun by many scholars working in a variety of fields (for examples, see Shepard 1967; Delcourt and Delcourt 1991; Pielou 1991; Turner and Meyer 1994; Loveland and Hutcheson 1995; subsequent chapters in this volume). Nevertheless, the effort to aggregate information from across the continent and to construct a relatively seamless timeline from studies focusing on different time periods and employing a variety of data sources and analytical approaches is a complex endeavor. Clearly, an international effort will be required, not only because different countries occupy the continent, but also because records of early changes, particularly from the time of European settlement, exist in museums and archives throughout the world. Researchers from universities, government agencies, and private institutions have begun this task. Completing it will require a clear set of objectives, a coordinated effort that encourages creative approaches, and substantial new investments. The costs will be repaid many times over through a deeper appreciation of the environment and improved environmental management.

The relationship between human civilization and nature is a complex and changing aspect of all ecosystems, and our understanding of that relationship is itself dynamic (see, for example, Cronon 1995). Recognition of the role of the human within the ecosystem, obvious and inescapable when most people hunted and gathered food or tilled the earth, has been largely lost in the developed world, where

links to nature are distant and abstract for the majority of the human population. We often see ourselves as being a step or more removed from nature, harvesting resources, recreating, monitoring impacts, interpreting conditions from the sidelines, and administering first aid to resuscitate an infirm world, when necessary. Donald Worster (1993) suggests that the way we use the land reflects our understanding of nature and our perceptions of ourselves. If widespread environmental degradation is an indication that our understanding of nature is narrow, it also suggests that so too is our perception of our own role in the functioning of natural systems.

An appreciation of history can widen and deepen this understanding. In 1906, American philosopher George Santayana warned that those who cannot remember the past are condemned to repeat it. But unlike the people who have faced social and political crises throughout the comparatively short history of civilization, those who ignore environmental history will not be blessed with the opportunity to repeat it. Instead, they will likely suffer through an increasingly difficult future, facing complex problems without the opportunity to consult the record of environmental change that stretches back, beyond the limits of human memory. Compiling this history and developing the tools to analyze, interpret, and share it broadly are important and inspiring missions as we enter the next millennium.

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Chapter 2: Historical Interrelationships Between Population Settlement and Farmland in the Conterminous United States, 1790 to 1992

by

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Abstract. The historical interrelationships between farmland and population settlement patterns have long been the subject of conjecture. Simple overlays of counties with historical population and farmland data, together with national soils and topographic data layers, provide a useful way to describe this delicate relationship spatially, as well as temporally. As new farmlands (cropland and grasslands) were being created at the population frontier early in the period between 1760 and 1992, certain other areas were being bypassed to be farmed only later when drainage and/or irrigation was possible. Other areas characterized by poor climate, steep slopes, and soils unable to support either cropland, pastureland, or grassland uses were unsustainably farmed or never farmed at all. Knowledge of land quality is key to understanding the interrelationship between populations and farmland. Urban expansion is preferentially converting prime farmland to non-agricultural uses. By 1992, metropolitan areas had expanded to engulf 25% (33 million ha or 82 million ac) of the prime farmlands in the Nation. This percentage was up from 20% (27.8 million ha or 68.6 million ac) of the prime farmlands in 1982. Population densities associated with farmland loss vary across the country but are quite specific at the local scale. For areas east of the Mississippi River, farmland decline historically occurred at an average population density of approximately one person per 9.3 ha (23 ac) of arable land. In the west, farmland decline began at average densities of one person per 35-486 ha (88-1,200 ac). This historical analysis provides helpful new insights into the capabilities of the Nation's natural resources to support competing land uses based on their performance over 230 years of population settlement.

Introduction: Reconstructing Patterns of Population and Agricultural Expansion

A close historical relationship between the geographical expansion of human population and progressive changes in rural land use can be demonstrated by examining databases derived from historical population and agricultural censuses. Understanding such trends may permit glimpses into the future of continuing changes in land-use patterns.

A number of questions are intertwined with population and agriculture interactions.

- What has been the relationship between the geographical spread of human populations and the simultaneous expansion of agriculture during the past 200 years?
- When, where, and why have certain areas been historically bypassed for agriculture?
- Has the phenomenal growth of large urban centers during the twentieth century been at the expense of some of our nation's best farmlands?
- Where are the remaining highest quality agricultural lands, and how can they be most effectively used/protected today and into the future for maximum, sustainable productivity?

We explored these questions by reconstructing historical patterns in the growth and expansion of human populations and agricultural activity across the United States over the past 230 years. Results of these analyses are presented in graphic format to illuminate the broad patterns and interrelationships. A series of maps and graphs depict changes in human population and agricultural activity across the continent. These images provide a visual introduction to large-scale temporal patterns in land-use history at the national scale.

Methods

Two historical databases—the Census of Population and Housing (starting in 1790) and the Agricultural Census (formally collected beginning in 1850)—provided a picture of the interrelationships between population and agriculture over time. Historical county-level data describing population and farming were collected from the Inter-university Consortium for Political and Social Research, University of Michigan, Ann Arbor. These data were processed at the Harvard Laboratory for Computer Graphics and Spatial Analysis to account for historical changes in county boundaries and the changing definition of farmland over time. Some adjustments to these data sets, acquired at various times and for different purposes, were necessary to permit the joint analysis and display of data at the resolution of counties.

Adjustments for Jurisdictional (County and State) Boundary Changes

Until 1910, new counties were often created, some were dropped, and new territories were acquired. In a few cases whole states seceded from other states or territories (West Virginia, for example, was created from part of Virginia in 1863 [U.S. Bureau of Census 1995]). For consistency, we used today's county boundaries and spatially allocated earlier data to them from earlier boundaries.

Census data were not available for some states until they joined the United States (e.g., those states involved in the Louisiana Purchase in 1803 and Florida, ceded by Spain in 1819 but not formally added to the conterminous United States until 1845). The late addition of Oklahoma is obvious in the images presented here, due to the lack of data for that state until after 1907. Consequently, there is some omission of early agricultural activity in the western states. Likewise, no spatial data exist for farming practices by Native Americans prior to European settlement. The reader should be aware of these data gaps when assessing the displays.

Changes in the Definition of "Farmland"

Until 1920, farmland in the censuses comprised both "improved" (tilled and in meadows) and "unimproved" (forests, woodlands, etc.) land. In 1920, farmland was defined by the U.S. Census as "land in farms as harvested croplands, idle croplands, pastureland, woodland not in pastureland, other farmland, and unimproved farmland." In 1930, "unimproved farmland" was redefined as "other farmlands." For data before 1920, only "improved" farmland was used as the definition of farmland. For census data describing farmland after 1920, the "land in farms" definition that also included "other farmlands" was used (U.S. Bureau of Census 1992, Appendix A:A2-A10). It is important to note that the definition of farmland used in this study is very broad and the study does not account for shifts of less- to more-intensive farmland uses, e.g., from rangeland into irrigated cropland uses such as has occurred in eastern Nebraska and western Kansas after 1970 (Gage and Maizel, unpublished data).

Cartographic displays of the data in maps presented here were developed further to allow us to spatially allocate population and farmland data to those areas within each county that would reasonably be expected to support these land uses (see historically non-farmed areas criteria below). County boundaries were thus intersected with the State Soils Geographic Data Base (STATSGO; Natural Resources Conservation Service 1991). These layers were then overlaid on a national 30-arc-second digital elevation model developed by the U.S. Geological Survey (USGS) of the U.S. Department of the Interior.

Because county size varies markedly across the United States, it would be misleading to compare counties based on the total number of acres under cultivation. Instead, the maps included here display agricultural activity as the percent of each county's land area that is farmland. Historical analyses of the county-level data showed that certain areas in the country were never or only transiently farmed. They were found to correspond to places where

- the topography has an average slope greater than 20%,
- soils are of the lowest agricultural quality for crop production as ranked by the NRCS Soils Capability Class system for cropland uses,
- soils have been classified by the NRCS as "barren," and
- less than 60% of the soils were rated as "good" for producing grasses as a rangeland wildlife habitat component.

In nearly every county, the maximum amount of farmland in production, as determined by the census, fell within the acreage declared "arable" by this method (data not shown). This result indicates that the criteria used to define nonarable land provide a reasonably accurate operational definition. Thus, farmland areas are shown within counties where soils and topography could reasonably be expected to support agriculture as cropland, pastureland, and/or rangeland. Because historically populated areas corresponded geographically to farmed areas, population data were allocated spatially to "arable" lands in the map displays. The graphics illustrating farmlands are superimposed on the USGS digital elevation model; thus the nonarable areas are rendered in grayscale illustrating elevation categories.

Certain figures generated for this project have been placed in the body of this report as they are discussed; however, an expanded understanding of temporal relationships can be derived if the entire series of graphics is examined in entirety. (See related site on the world wide web, http://biology.usgs.gov/luhna/ncri/images.html for graphics illustrating and animating the population by county for 1790, 1800, 1810, 1820, 1830, 1840, 1850, 1860, 1870, 1880, 1890, 1900, 1910, 1920, 1930, 1940, 1950, 1960,1970, and 1990, and for graphics illustrating percent farmland by county for 1850, 1860, 1880, 1890, 1900, 1910, 1920, 1930, 1940, 1950, 1982, 1987, and 1992.)

Results and Discussion

Early Population Settlement and the Farmland Frontier (1790-1860)

In 1790, the U.S. population in the original 13 states was 3.82 million people (Fig. 2-1). By 1850, the population had increased nearly tenfold, to 23 million (Fig. 2-2), and by then, according to the U.S. Census of Agriculture, there were 118 million ha (292 million ac) of land in farms (Fig. 2-3).

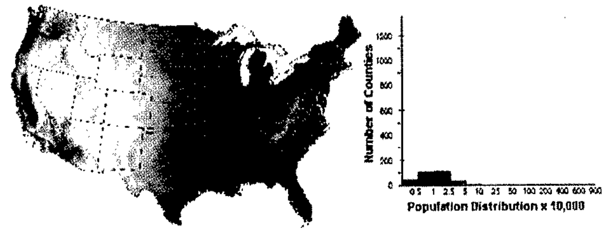

Fig. 2-1. Population, 1790.

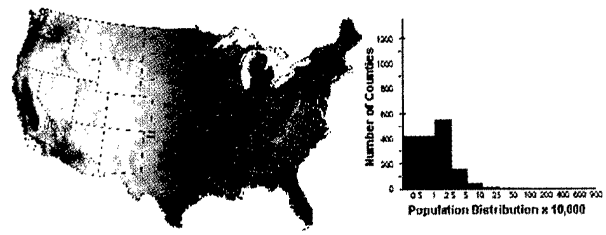

Fig. 2-2. Population, 1850.

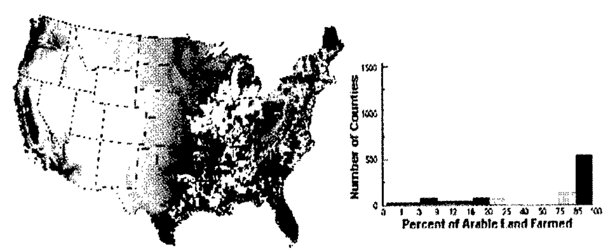

Fig. 2-3. Percent of land in farms by county, 1850.

The average population density was approximately 1 person per 5 ha (13 ac) of farmland. Most of the population was concentrated in the cities of Charleston and Greenville, South Carolina; Augusta, Georgia; Fayetteville, North Carolina; Danville and Charlottesville, Virginia; Lancaster, Pennsylvania; Trenton, New Jersey; Albany and Rochester, New York; and Worcester, Massachusetts.

By 1860, large agricultural regions averaging 202,000–324,000 ha (500,000–800,000 ac) per county developed around these urbanized areas, and more diffuse but significant population settlements averaging 5,000–25,000 people per county had already begun extending westward across Pennsylvania into Ohio, Indiana, Illinois, Iowa, and southern Wisconsin (Fig. 2-4). Smaller frontier populations averaging 2,000 people per county were also settling new farmlands averaging 8,000–20,000 ha (20,000–50,000 ac) per county in eastern Missouri and eastern Texas (Fig. 2-5).

As eastern cities continued to grow, Philadelphia became the largest city in the United States in 1860 when its population surpassed 500,000. By that time, the total U.S. population had increased to 31.1 million.

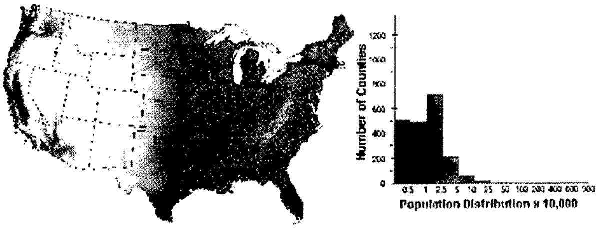

Fig. 2-4. Population, 1860.

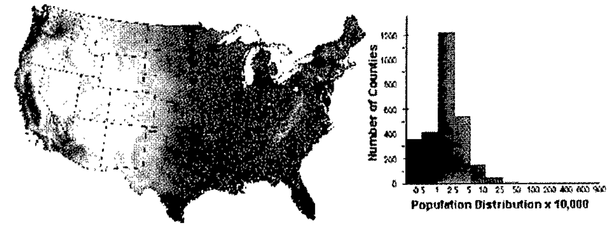

Fig. 2-6. Population, 1900.

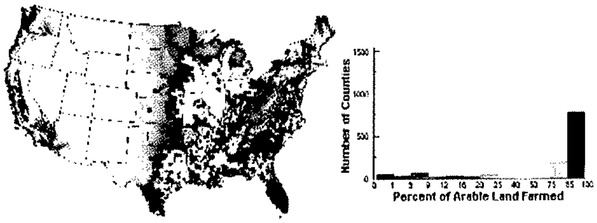

Fig. 2-5. Percent of land in farms by county, 1860.

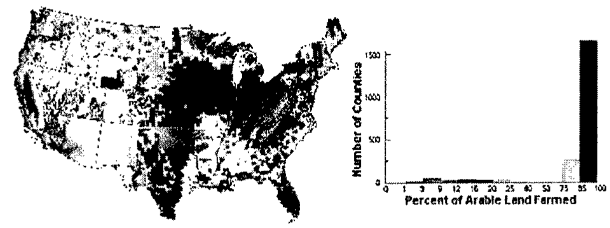

Fig. 2-7. Percent of land in farms by county, 1900.

From 1850 to 1860, counties with the largest amounts of land in farms (0.2 million to 0.4 million ha or 0.5 million to 1.0 million acres) were still found mostly in eastern areas, especially in plantations in South Carolina and large farms in the Northeast. By that time, agriculture had already gained a foothold on the west coast in the Willamette Valley of Oregon.

In 1890, the census reported for the first time population and farmland expansions following the annexation of Texas in 1845 and the ceding of southern California to the United States by Mexico in 1848. Of course, expansion of farmland across the United States was not a uniform process. Although Tampa-St. Petersburg, Florida, was an established population center by 1900, only the northern part of the state had been settled (Fig. 2-6). Farmland development in the southern part of the state, with its extensive wetlands, awaited access via new roads and the drainage practices and irrigation technologies that arrived in the early 1930's (Fig. 2-7).

Translocation of Large Farming Areas from East to West (1850-1950)

By 1900, coastal California farming had spread inland into the California Valley. New farming areas had become established in the coastal region of northwestern Washington, and large ranching areas were operating in Wyoming, Montana, and southwestern Washington. Large new farming and ranching areas were also being established in central Texas, Kansas, Nebraska, Illinois, and the Dakotas by 1900. By this time however, the largest early farm/plantation areas in South Carolina had begun to decline. In just 50 years, 15 major cities in the Northeast had reached populations of more than 500,000.

By 1950, a new wave of large frontier farms had rolled westward, past the Mississippi River and into eastern Colorado and southwestern Texas, and northward to the Dakotas, creating patterns that remain today (Figs. 2-8 and 2-9). These areas are now—as they were then—largely rangelands, with soils capable of supporting grasslands for livestock grazing. More recently, irrigation has resulted in significant cropland development in certain sections of these areas.

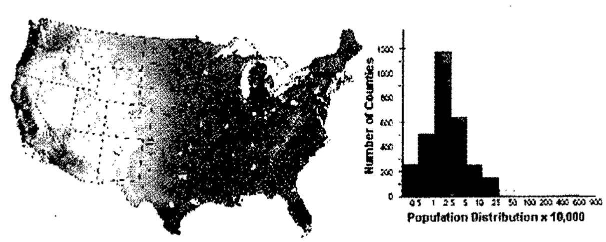

Fig. 2-8. Population, 1950.

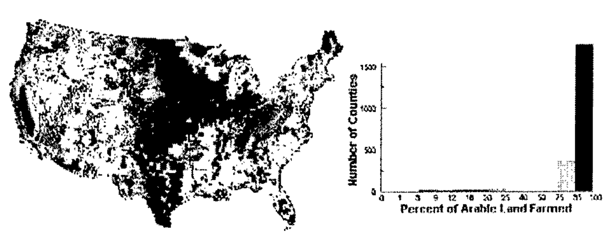

Fig. 2-9. Percent of land in farms by county, 1950.

Land Quality and Historical Farmland Patterns: Historically Unsustainably Farmed Areas

A review of the progression of percentage of land in cultivation from 1850 through 1992 reveals some notable regions where farming occurs only transiently, in small areas, or not at all. These areas are distinguished from those designated as nonarable, such as parts of southern Florida, which were put into production late in the period of population expansion. We dubbed these areas "historically unsustainably-farmed." These areas include, for example, parts of northern Michigan, Wisconsin, northern Minnesota, and western Nebraska. In these areas there were rarely more than 30,000 ha (75,000 ac) per county in production. Today these areas have approximately 800 ha (2,000 ac) or less per county in farmland. Modern soils data show that several soil- and water-related characteristics limit productivity over many of these unsustainably farmed areas, including the presence of wetlands, poor quality soils for agricultural production, steep slopes, sandy soils, lack of water, and poor climatic conditions.

In the case of the areas across northern Michigan, Wisconsin, and Minnesota, the poor quality of soils, presence of wetlands, and shorter growing season have all contributed to their being historically abandoned or altogether bypassed by farmers. In western Nebraska the widespread existence of deep, sandy soils, in combination with more arid conditions had already imposed a severe limitation on agricultural development.

In addition to the prohibitively arid regions of the desert West, many additional locations have been historically bypassed by agriculture for one or more of the above reasons. A careful review of the images of percent land in farms from 1850 through 1992 reveal 25 of these unfarmed or abandoned farming areas (Table 2-1).

Prime Farmland Under Urban Influence and the Urban/Agriculture Interface

As populations expanded rapidly between 1900 and 1950, some farming areas in the East showed early signs of decline, although farmland continued to increase in Florida. Between 1950 and 1992, even greater declines in farmland occurred in the East as the total U.S. population increased from 149.7 million in 1950 to 248.7 million in 1990. This trend is particularly noticeable in the images around the burgeoning cities of Boston, New York, Rochester, Buffalo, Philadelphia-Trenton, the Baltimore-Washington corridor, Richmond, and areas near Cleveland, Detroit, Chicago, and Cincinnati. Farmland in the west coast urban areas surrounding Los Angeles, San Francisco, Portland, and Seattle had also begun to decline (Fig. 2-10).

In 1952, 169 of the more than 3,000 counties in the conterminous United States had no farmland at all. In 1982, this number had increased to 177, and in 1992, to 185 counties. Of the remaining counties with farmland, 2,241 lost 10% or more of their farmland beginning at various times after 1950. This trend generally occurred when populations exceeded an average of one person per 9.3 ha (23 ac) in counties east of the 100th meridian and one person per 35-486 ha (88-1,200 ac) in those counties losing farmland west of the 100th meridian.

But the whole story is not told by numbers of hectares or acres alone. Of the 137 million ha (339 million ac) of prime farmland (for definition see the National Soil Survey Handbook [Soil Survey Staff, Natural Resources Conservation Service 1997]) in the United States in 1982, 27.8 million ha (68.6 million ac; approximately 20% of the total) were considered by the Census Bureau to be under urban influence—that is, inside Metropolitan Statistical Areas (MSA's; for definition see [U.S. Bureau of Census 1995]).

By 1992, MSA's had expanded to engulf 33 million ha (82 million ac) of prime farmland, while the total number of prime farmland hectares nationwide had declined from 137 million (340 million ac) in 1982 to 133 (330 million ac) in 1992 (Fig. 2-11).

One can conclude from the evidence above that a significant portion of the Nation's prime farmlands has been lost to metropolitan development in the past 100 years. A more detailed look at this trend can be found in Imhoff et al. (Chapter 3, this volume), where nighttime satellite images of the earth are compared "spot for spot" on the ground with census data and soils maps. The results clearly show that "urban sprawl" has resulted in conversion of productive agricultural soils to nonagricultural use.

Conclusion

This study has illuminated answers to parts of the four questions posed in the Introduction. Spatial data sets, and new techniques for analyzing and visualizing these data, will permit a greater understanding of the past trends and therefore a better anticipation of future land use and landcover changes, such as those that are currently emerging from the tensions at the urban and agriculture interface. For instance, this study shows that issues surrounding population and farmland ratios related to farmland creation and decline are highly dependent upon the quality of the farmland and its ability to sustain food production needs. Until land quality (among other factors) is incorporated into the urban and agriculture interface issue as a widely accepted determinant, conjecture that differs by broad geographies (for instance, as eastern and western views) will only continue.

As Federal, State, and local land managers better understand the interaction of population growth, urbanization, and agricultural activity, they will be better able to make informed decisions regarding resource conservation, development, and land use. Among the key challenges will be the preservation of the nation's remaining productive agricultural areas.

Table 2-1. Large, historically non-farmed or unsustainably-farmed regions in the United States.

Hectares (millions)	Acres (millions)	State(s)	Forest [a] (percent)	Federal [b] (percent)	Principal Limitations [c]
0.57	1.40	New York	90	0	Class 6,7 soils
0.51	1.25	Florida	0	10	Wetlands; class 7 soils
1.81	4.48	Florida & Georgia	70	10	Wetlands; class 5,6 soils; restricted root zone
1.56	3.85	Florida panhandle	30	30	Wetlands; class 8 soils; restricted root zone, low fertility soils
0.70	1.73	Pennsylvania	40	50	Unknown
2.59	6.40	West Virginia & Kentucky	90	0	Class 7 soils
0.47	1.15	South Carolina	60	0	Unknown
0.86	2.12	W/central Georgia	85	0	One-third area, 7%-15% wetlands
1.87	4.61	Georgia	85	10	One-fifth area, 7%-20% wetlands; low fertility soils
1.82	4.50	Georgia & South Carolina	33-70	50	Class 7 soils
1.92	4.74	Alabama	90	5	Class 7 soils
0.96	2.37	Mississippi	70	50	Common flooding
1.76	4.35	Louisiana	50-60 in the north	0	Common flooding
0.88	2.18	Texas	90	5	Class 7 soils; one-tenth 20% wetlands; low fertility soils
1.42	3.52	Arkansas & Louisiana	90	0	Class 6 soils; low fertility in western part
1.24	3.07	Missouri & Arkansas	0	10	Unknown
2.33	5.76	Michigan	80	20	One-third area 7%-30% wetlands; class 6,7 soils
6.731	6.64	Wisconsin, Minnesota & Michigan	85	40	Class 6,7 soils; wetlands; low fertility
0.98	2.43	Colorado	0	60	Class 6 soils
0.43	1.09	Colorado	0	50	70% class 7 soils
3.62	8.96	Idaho	0	90	One-tenth area 10% wetlands
2.33	5.76	Idaho & Montana	90	30	Class 7 soils
1.94	4.80	Nevada	0	20	70%-80% class 7 soils, 40% class 8 soils; barren land
0.78	1.92	California	0	90	Class 7 soils
1.04	2.56	Oregon & California	80	30	Class 7 soils
3.88	9.60	Washington & Oregon	80	50	One-fifth area 7%-20% wetlands; class 6 soils
45.00	**111.24**	**Total**			

[a]On non-federal lands in the region.
[b]Federal jurisdictions include National Parks, National Forests, National Wildlife Preserves, and other lands under Federal jurisdiction.
[c]Classes for soils are from the Soils Capability Classes (Soil Survey Staff, Natural Resources Conservation Service 1997). These are interpretations of the soils in terms of their ability to support cropland and certain pastureland uses. Lowest numbers (e.g., 1) have highest agricultural value, and highest numbers (e.g., 8) have lowest value.

Through integration of historical databases from many different sources and the continuing refinement of the resolution and accuracy of this diverse information, we hope to continue to improve our understanding of shifting patterns of land use and its relationship to human settlement and population growth. This integration and refinement should permit the untangling of the complex local interactions among a host of factors influencing agricultural activity. These factors include land quality, farm and human settlement patterns, farming types and economics, physical and biological constraints, and socioeconomic characteristics of farms and farmers in the specific context of their local communities. We anticipate that this new way of evaluating historic information will be used to better understand the impacts on farmland as a result of future growth planning, such as has been developed for the Washington, D.C., region (Maizel and Muehlbach 1998).

Acknowledgments

Some of the information in this chapter was assembled for a project developed at the American Farmland Trust: M. Maizel, J. Corson-Rikert, Kelly Chan and R. Denis White (1988), "Historical Land Use in the United States," as funded by a grant from the Laurel Foundation of Pennsylvania.

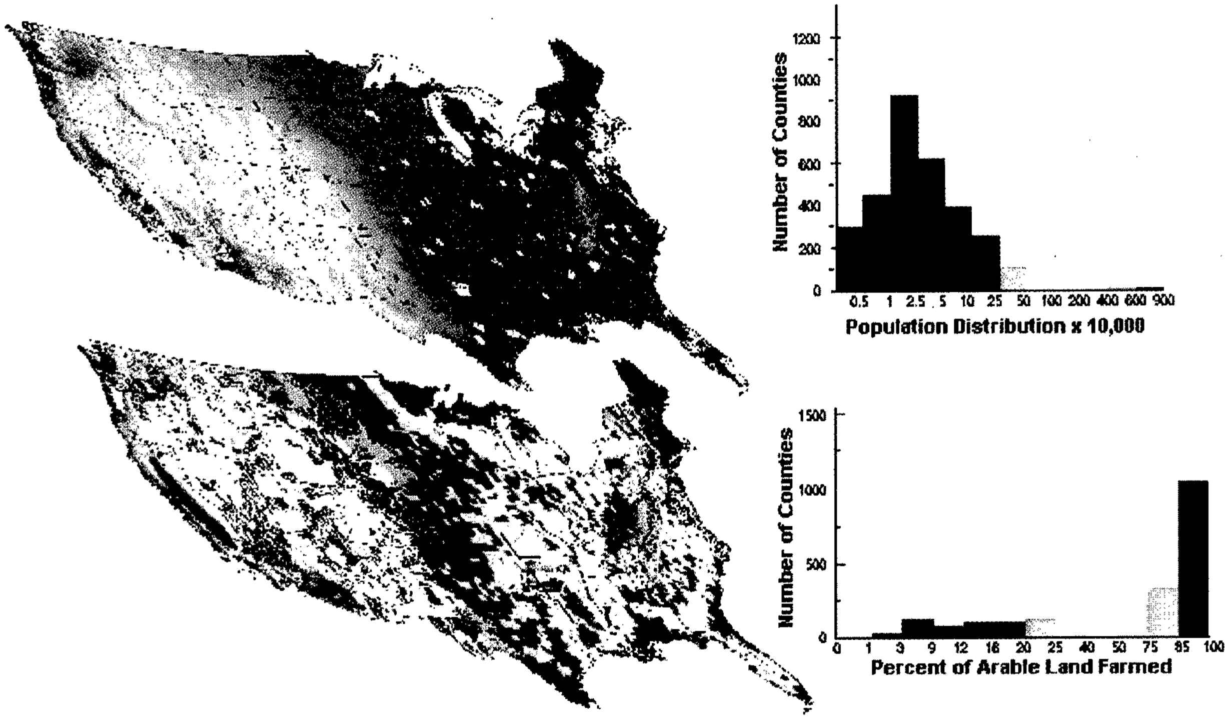

Fig. 2-10. Population, 1990, and percent of land in farms by county, 1992.

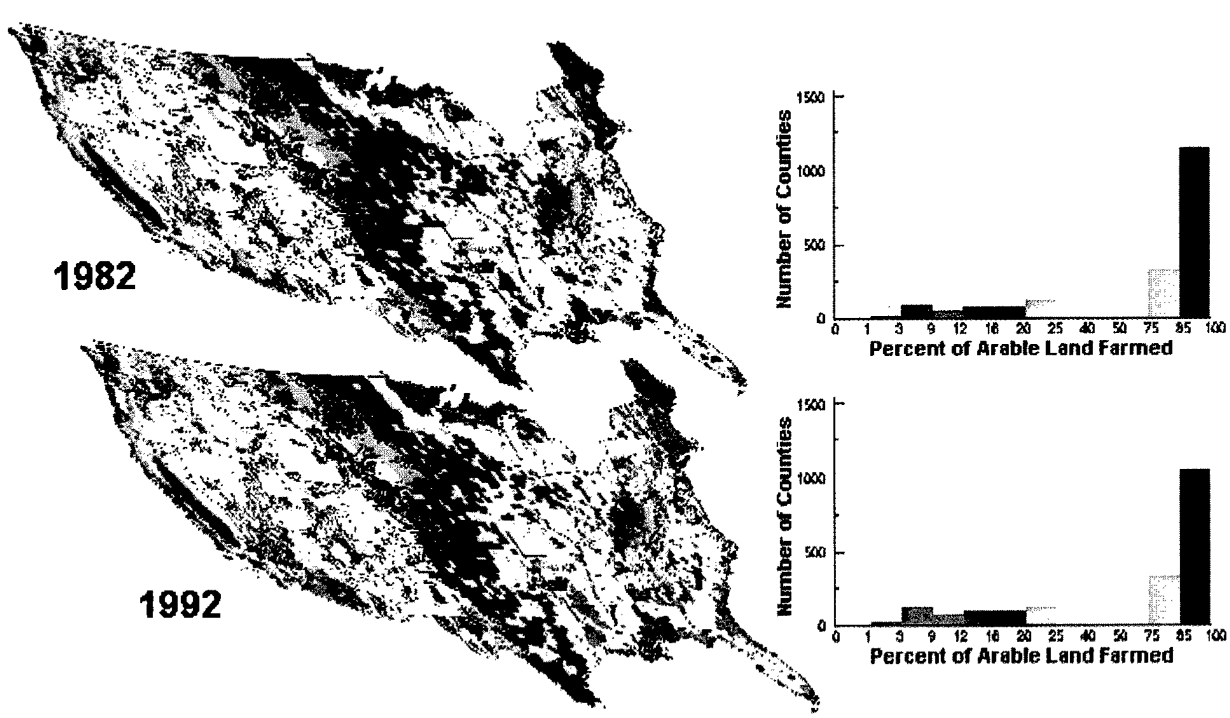

Fig. 2-11. Percent of land in farms by county, 1982 and 1992.

The project was inspired by a hologram depicting historical population growth and expansion in the United States as constructed by Geoff Dutton when he was at the Harvard Laboratory for Computer Graphics and Spatial Analysis in the late 1970s. In addition, special recognition is due to Jonathan Corson-Rikert for work in reconciling historical changes in county boundaries and farmland definitions.

Images for this chapter were contributed by the Biological Systems Under Stress and Change Consortium, a collaborative initiative among four of the authors (Maizel, White, Gage, and Osborne) to integrate information about biological and physical resources in spatially hierarchical information systems in order to better understand interrelationships between natural and human-managed systems.

The National Center for Resource Innovations-Chesapeake, Inc., is a founding member of the National Center for Resource Innovations, a consortium of seven project sites established in 1990 by Congressional appropriation through the U.S. Department of Agriculture's Cooperative State Research Education and Extension Service. NCRI's mission is to build geographic information system-based information systems for public policy and other decision makers. The National Center for Resource Innovations-Chesapeake specializes in integrating spatially hierarchical data from many public and private sources, "From the Nation to the Neighborhood," in order to build new information about interactions between human population and the status, use, and potential of the Nation's natural resources and farming systems.

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Chapter 3: Assessing the Impact of Urban Sprawl on Soil Resources in the United States Using Nighttime "City Lights" Satellite Images and Digital Soils Maps

by

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Abstract. Nighttime satellite images of the Earth showing city lights were merged with census data and a digital soils map in an effort to estimate the extent of developed land in the United States and the impact of development on soil resources. The urban areas defined by "city lights" had mean population densities of 1,033 persons/km^2 and 427 housing units/km^2 (4.13 persons and 1.7 households/acre). Urban areas accounted for 2.7% of the surface area in the United States, an area approximately equal to the state of Minnesota or one-half the size of California. A United Nations Food and Agriculture Organization soils map of the United States was overlaid on the nighttime "city lights" image to determine which soil types are most impacted by development. The more limiting factors a soil has, the more difficult or expensive it is to farm; consequently a soil fertility classification system based on physical factors that limit agricultural production was used to rank soils. Results for the United States show that the residential, commercial, and industrial development, known as "urban sprawl," appears to be following soil resources, with the better agricultural soils being the most affected. Some unique soil types appear to be on the verge of being entirely covered by urban sprawl. The conversion of good agricultural soils to nonagricultural use may have long-term ramifications for sustainable development at the local, regional, and global levels.

Introduction

The postagricultural growth of human populations, combined with technological advancement, has led to the widespread transformation of natural ecosystems into those dominated and heavily managed by human beings. The potential impact of this process on Earth's biological and geochemical systems is a current subject of debate, and concerns range from those dealing with biosphere-atmosphere interactions and global climate change (Kates et al. 1990) to the preservation of biodiversity, sustainable development, economics, and agricultural productivity (Vitousek et al. 1986; Ehrlich and Wilson 1991; Raven 1991; Ehrlich et al. 1995).

The conversion of natural systems to agricultural production has been the primary basis for the successful growth of human populations for the last 9,000 years (Kates et al. 1990). The conflict between urban and agricultural land use, however, is only now becoming a subject of controversy. The transformation of productive agricultural land to urban use under burgeoning populations has become a contentious element in debates over sustainable development and food security (Ehrlich 1989; Daily and Ehrlich 1992; Ehrlich and Ehrlich 1992). As more land is converted to urban uses, the question arises as to whether this trend represents a systematic reduction in our ability to produce food by placing our infrastructure on the most productive soil resources. A disturbing consequence of this urbanization process is a growing dependence on ever greater yields per unit area (on soils that remain) or a reliance on more distant soil resources and agricultural production.

Given present demographic trends, it is important that issues of agricultural versus urban land use be resolved. An increasing number of regional populations may be at risk of food shortages in the future as a result of sociopolitical and economic instability (e.g., war, economic depression, social upheaval, etc.) with their consequent effects on global food supplies. While the reality of some agricultural land loss is accepted, both the magnitude and the potential effect are hotly debated. Central to much of the debate is the difficulty in acquiring accurate measurements of the area of urban land use, monitoring changes in urban land use, and assessing the impact of these changes on agricultural land area or production in a way that can be used in rational, cost-beneficial analyses (Parsons 1977; Meyers and Simon 1994).

Mapping Urban Sprawl Using Remote Sensing

Surprisingly, measuring the extent of urbanization using conventional methods has been difficult, even in the United States where modern census procedures are used. In 1977 for example, the U.S. Department of Agriculture (USDA) announced figures concerning the loss of agricultural land in the United States due to urban sprawl. The figures, which were derived by using census data, sparked a controversy which resulted in two significant revisions between 1977 and 1987 before finally being set at a total area of 116.4 million hectares of land converted to urban use (Meyers and Simon 1994). Thus, census data are a valuable resource but their interpretation is controversial, i.e., they are not a substitute for direct observations of the land surface.

The use of satellite remote sensing is an obvious alternative for detecting and monitoring global change and for classifying land-use transformation. Satellite sensors such as the Advanced Very High Resolution Radiometer (AVHRR), Landsat Thematic Mapper (TM), and the French SPOT system have been used successfully for measuring deforestation, biomass burning, and other landcover changes including the expansion and contraction of deserts (Skole and Tucker 1993; Tucker et al. 1991; Sellers et al. 1995). However, remote sensing techniques are just beginning to be used to monitor the conversion of agricultural land to infrastructure (i.e., the process of urbanization). Land conversion to urban, suburban, or commercial and industrial use is one of the land-use processes most disruptive to vegetation. Yet urbanization is a difficult process to measure on a global scale because the spectrally diverse landcover types found within urbanized areas are easily confused with nonurban areas when interpreting satellite data. In addition, coarse-resolution data sets (pixels > 1 km^2) have inadequate spatial and spectral resolution for reliably determining urban infrastructure, while the higher resolution data sets (100 - 1,000 m^2) present problems of analysis due to the vast data volumes required for processing, high costs of acquisition, and difficulties in automating interpretation. Most remote sensing literature dealing with urban areas emphasizes detection and mapping of traditional land-use/landcover types using high-resolution image data sources such as SPOT and/or Landsat TM data (Ridd 1995). Although some mapping of urban areas has been done with lower resolution sensors such as AVHRR (Ridd 1995), the development of techniques to accurately identify urban lands using this system is still in its infancy.

New satellite imaging approaches are needed to provide accurate information about the location and extent of human habitation and urbanization at regional, continental, and global scales. One approach uses nighttime satellite data sets as a means of detecting and mapping urban land use and merging those data sets with soils maps to estimate the potential impact of urbanization on basic soil resources. Nighttime images of the Earth acquired at visible wavelengths by the Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) provide a dramatic picture of urbanization through the detection of city lights as they are seen from space (Kramer 1994; Elvidge et al. 1997; Fig. 3-1). The stark contrast between lighted and unlighted lands provided by this type of

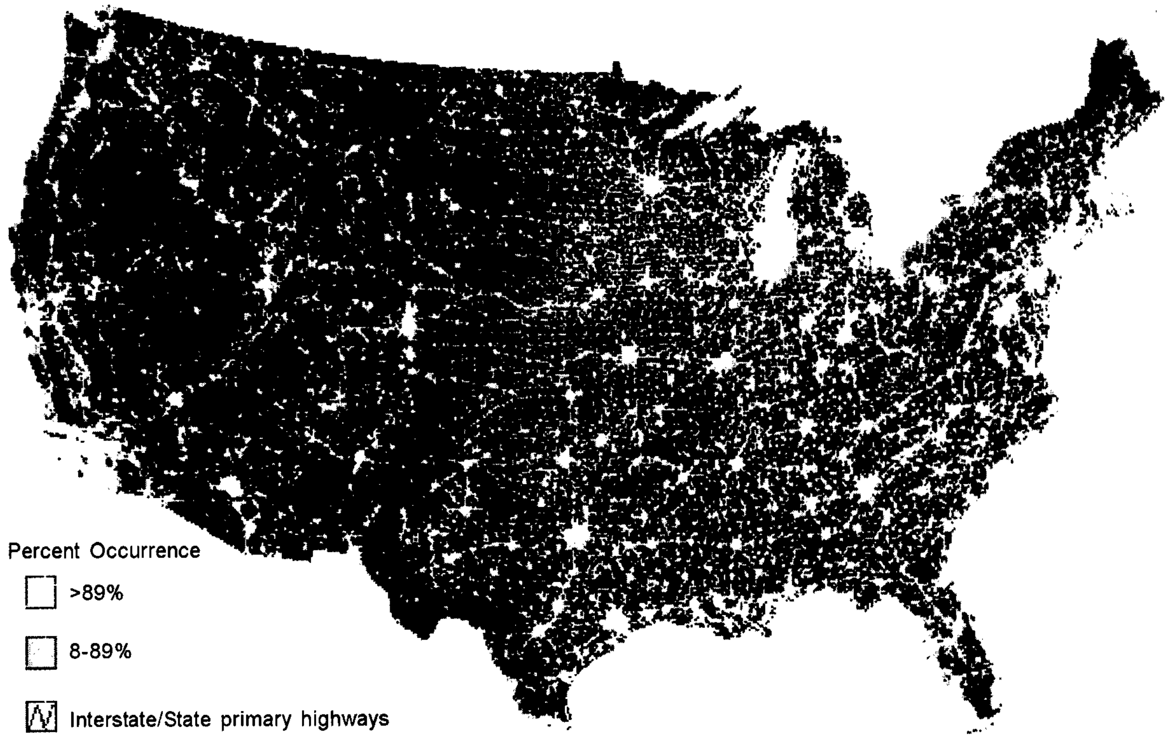

Fig. 3-1. Nighttime "city lights" image for the continental United States derived from a 231-orbit composite of the U.S. Air Force Defense Meteorological Satellite Program's Optical Linescan System. The nation's highway system is overlaid on the image. Urban areas are shown as yellow and represent areas heavily lit at night as observed from the satellite.

image, combined with the sensor's moderate spatial resolution (2.6 km) and large area covered per scene, makes it an obvious choice for classifying and mapping land transformation to urban and suburban uses over large areas.

Methods

Satellite data acquired at night from the DMSP/OLS were merged in a computer with digitized soils maps and census data to make a first approximation of how urban land use in the United States may be affecting agricultural potential. Merging the data sets allowed us to look at how each data set related to the other, much like overlaying map transparencies on top of each other. In this way, we could overlay the "city lights" images on the soils maps to examine whether or not the most productive soils were being lost to urban sprawl. Results of a continental overview of the conterminous United States (lower 48) and regional analyses for California, Illinois, Wisconsin, and Florida—the four states with the largest agricultural economies ranked by total market value of products according to the 1987 U.S. Census of Agriculture—are described in this chapter (see Imhoff et al. 1997a, 1997b).

Nighttime Views of the Earth from the DMSP/OLS Satellite (City Lights)

The DMSP/OLS satellite sensor is sensitive to very low intensity light sources, including city lights, lightning, moonlit clouds, fires, and other bright surfaces. The sensor was originally designed to allow the observation of moonlit cloud cover for meteorological forecasting and nighttime flight operations by the U.S. Air Force. Pointed down at Earth's surface, this satellite sensor takes dramatic pictures of Earth's cities on new moon nights when the city lights are the brightest objects on the surface. A "city lights" data set based on this sensor is particularly attractive because it allows easy identification of lit and nonlit places, which correspond to heavily populated and less populated areas (see Welch 1980; Welch and Zupko 1980).

The satellite image data set used here is a composite generated by the National Oceanic and Atmospheric Administration (NOAA) from over 230 cloud-free nighttime images of the United States gathered between 1994 and 1995 (Elvidge et al. 1997). After some initial processing, a final map product (Fig. 3-1) was generated. The final map product compared very favorably with census estimates of urban area in the United States (Imhoff 1997b).

In order to determine what housing and population densities are found in the lit urban areas on the "city lights" satellite image, we merged United States census data on housing density and population for a number of large metropolitan areas with the satellite data. The housing and population density statistical information was extracted from the 1990 Census of Population and Housing and associated maps (U.S. Bureau of the Census 1991, 1992). Merging census and satellite data allowed us to "tag" the lit areas on the nighttime satellite image with numbers on population and housing density. The mean housing density for the urban (lit) areas was 427 housing units/km^2 and the mean population density was 1,033 persons/km^2. Since the population and housing density of the lit areas almost certainly precludes major agricultural production beyond small home gardens and subsistence agriculture, we classified these areas as being lost to large-scale agricultural production.

Assessing Soil Resources–What Makes One Soil Better Than Another?

In order to assess the soil resources of the United States, we chose to make our first estimate using the United Nations Food and Agriculture Organization's (UNFAO) Digital Soils Map of the World (1975, 1992). At present, the UNFAO map is the only global digital soils database available. While it is coarse in resolution (1:5,000,000), it has been used extensively in global- and continental-scale analyses of terrestrial resources, biological processes, and global change (Potter et al. 1993, 1994). While other, finer scale digital soils maps are available for the United States, they are not available for all parts of the globe. We selected the UNFAO map so we could compare the U.S. results with those from the rest of the world for an analysis of global food security.

The UNFAO soils map identifies approximately 315 soil units for the United States based on their physical and chemical composition, their topographic situation, and the local climate. The soil units were ranked using a soil fertility index known as the Fertility Capability Classification (FCC) system (Buol et al. 1974; Sanchez et al. 1982). This system provides a basis for comparing and rating soils world-wide for their suitability for agricultural use. The ranking system assesses the textural, structural, chemical, and climatic characteristics of the soil that have a direct relationship to fertilizer, plowing, and irrigation requirements for successful farming. The FCC system assigns condition modifiers, or limiting factors, to each soil type, if any are present. Condition modifiers include such factors as dry or seasonally dry conditions, low cation exchange capacity (CEC), aluminum toxicity, acidity, iron and phosphorus fixation, gleying, basic reaction, potassium deficiency, salinity, etc. As the number of limiting factors present in a soil unit increases, so does the cost of agricultural production, because the limiting factors need to be overcome through liming, irrigation, fertilization, or other processes. In a sense, ranking the soils by the number of limiting factors is like an economic rating of the costs required to farm a plot of land. The best soils are those with the fewest limiting factors or with those factors most easily and cheaply overcome. A soil with no limiting factors is good for farming as-it-already-is—there is no need to add to it to make crops grow. Soils with many limiting factors may be prohibitively expensive to farm. While not perfect, the FCC system can be quickly applied to the UNFAO soils maps and can be interpreted as a surrogate "native soil productivity" rating for agriculture.

For our analysis, we ranked soil units in the United States as ranging from those having zero or no limiting factors to those with eight limiting factors. Soils with no limiting factors are the best soils for agriculture (in terms of least cost of production), and soils with seven or eight limiting factors were considered nearly impossible to cultivate because of the presence of a cumulative number of impediments (dry, saline conditions, shallow soils, high slope, etc.). Looking at the soils data for North America, it must be said that the United States contains a lot of good soils within its borders (Fig. 3-2). About 53% of the total soil area of the United States is made up of soils with two or fewer limiting factors, and over 90% of the country is composed of soils with four or fewer limiting factors. While some limiting factors are more economically significant than others, the United States is still capable of impressive agricultural production relative to the rest of the world. Many countries in the world have relatively few soils with two or fewer limiting factors and are forced to farm soils with many obstacles. The huge investment in terracing hillsides in China is an extreme example of attempts to overcome the limiting factor of severe slope.

Results and Discussion

An estimate of urban land use and its impact on agricultural soil resources was made by classifying the "city lights" images into urban and nonurban land use classes and then comparing them to the fertility-ranked soils map. The amount of soil area in urban use (under city lights) was calculated for each soil type mapped for the entire conterminous United States. Any soil units found under the "city lights" were considered to be in urban use and therefore unavailable to mechanized agriculture. The soil units under "city lights" were assessed individually (all 315 units separately) and then grouped by the number of FCC limiting factors they had (nine classes: zero to eight limitations). An additional computer map overlay showing state boundaries was used to select data for individual states for a more localized view of soil losses due to urban sprawl.

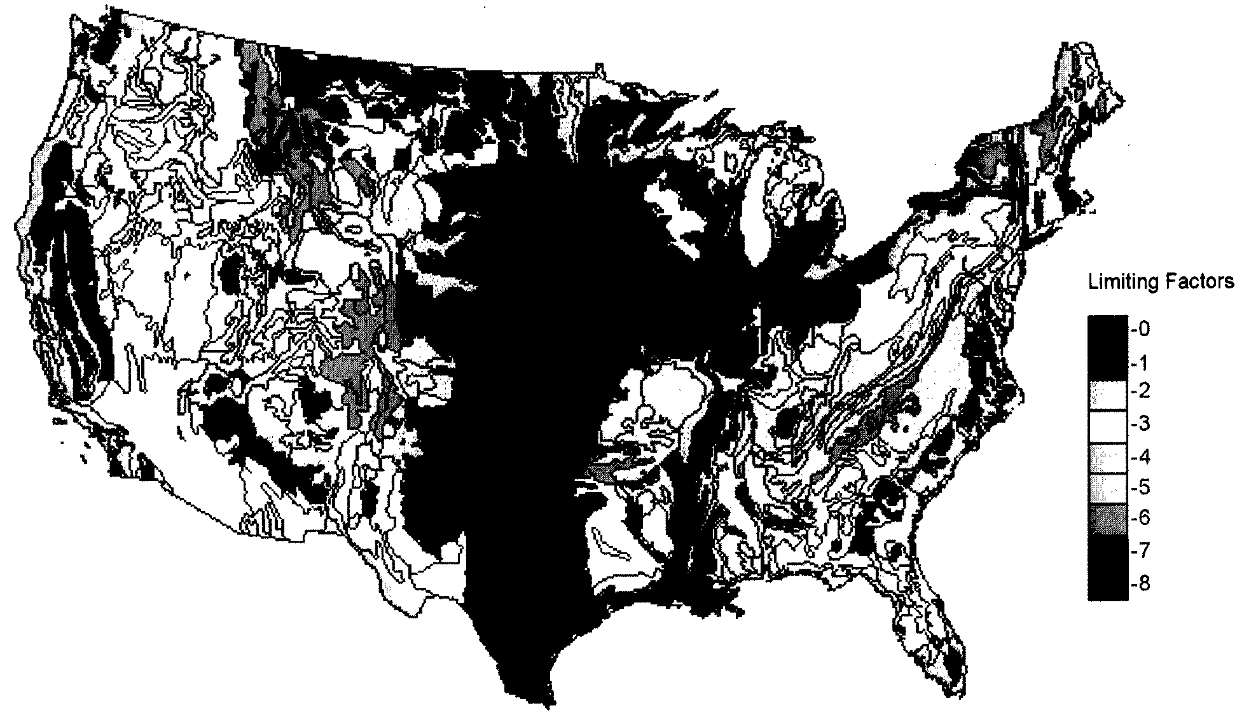

Fig. 3-2. A soils map of the United States created from the United Nations Food and Agriculture Organization digital soils map of the world. Soils are classified by their number of agronomic limiting factors. Soils with a high number of limiting factors are problematic and require remediation for agricultural production. The best soils for agriculture have no or few limiting factors.

Urban Occupation of Soils in the United States

By our satellite-based assessment, about 2.67% of the total land area of the conterminous United States is now in urban use. While this may seem like a small area, if all of this urban/suburban or commercial/industrial land were coalesced into a single entity, it would be a city the size of the entire state of Minnesota or a city that would occupy all of California from San Jose to San Diego. Furthermore, when considering the effects of land conversion, it is important to address the issue of quantity versus quality. For example, in our analysis, only about 3% of the land surface is urbanized, but the best soils are being developed first. If the situation is examined from a continental scale, it is clear that the percentage of the land in development generally increases as the number of limiting factors decreases (Fig. 3-3; Table 3-1). These findings support the argument that the best soils are the first victims of urban sprawl. There is evidence, however, that some preservation of the very best soils may be taking place. For example, the graph shows that soils with no limiting factors (i.e., the very best agricultural soils) are a little less developed (2% urban) than the soils with one limiting factor (4.22% urban). If it is true that this is evidence of preservation of the very best soils, however, it is also true that it is happening at the expense of the second best agricultural soils.

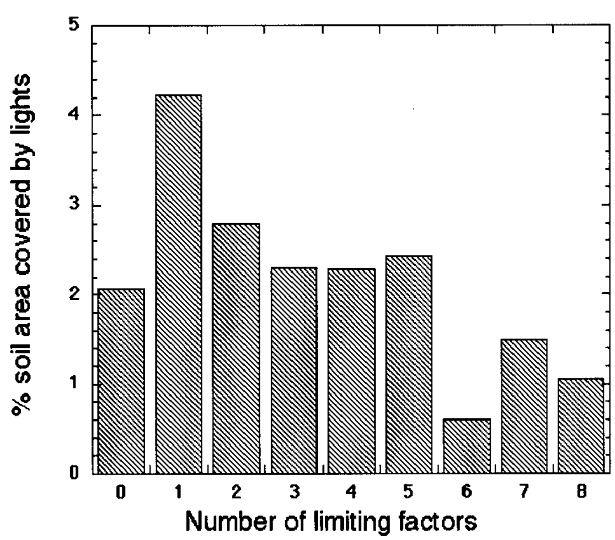

Fig. 3-3. Percent of soil area covered by lights in the United States. The soils are grouped into nine classes depending on the number of limiting factors they have. The greater the number of limiting factors, the more effort required to use a given soil unit for agriculture. The soils with fewer limiting factors are bearing the brunt of urbanization, but soils with zero limits are less urbanized than others, possibly giving evidence of marginal preservation.

Since these soils often exist closely to one another, it is understandable that if the best soils are protected, development

Table 3-1. U.S. soils (United Nations Food and Agriculture Organization) grouped by number of physical factors limiting agricultural production.

Number of limiting factors	Total area of soil class (km²)	Soil area covered by lights (km²)	% soil area covered by lights	% urban area from 1990 census
0	1,282,805	26,558	2.07	
1	1,663,218	70,248	4.22	
2	1,172,880	32,723	2.79	
3	1,608,131	37,060	2.30	
4	1,353,633	30,872	2.28	
5	216,542	5,267	2.43	
6	309,090	1,846	0.60	
7	15,681	233	1.49	
8	93,234	979	1.05	
Totals	**7,715,214[a]**	**205,786[b]**	**2.67**	**2.9[c] (222,977 km²)**

[a]Total areas for satellite data do not include water bodies or Hawaii and Alaska.
[b]2.67% of conterminous United States is covered by lights.
[c]From 1990 Census of Population and Housing, incorporated cities and towns with population greater than 2,500.

would be pushed onto the soils immediately around them. It then becomes important to address the question of how soils are distributed locally and what constitutes the "best" agricultural soils in a specific region. For example, in Fig. 3-3, which shows all the soils in the United States grouped together by limiting factors, urban development appears to be more or less evenly distributed across soils with two, three, or four limiting factors. This observation would lead one to believe that development is mostly taking place on soils with less agricultural capacity. What is not evident in this graph (or at the national level), however, is that in many parts of the country, soils with two, three, or four limiting factors *are* the "best" agricultural soils in those regions. Any loss of those soils could lead to significant reduction in agricultural potential there. California offers a prime example of this situation, where the soils of the central valley all have one limiting factor, yet they are the most important agricultural soils in the state and perhaps the entire United States.

It is not unusual that the best soils should fall to urban development. Most major cities of the world are located on or near river flood plains or deltas, which are also the most productive farming areas. Unfortunately, poorly rated soils are often unsuitable not only for agriculture but also for construction because of steep slopes or other limiting physical factors. The economics of urbanization, however, make it easier to overcome some soil-related problems.

Another result of this analysis is the apparent loss of unique soil types. The pressure of urban sprawl is not equally distributed over all of the soil types. For example, between 50% and 70% of some FAO soil units (types) are now in urban use. Two mesic humid soils suitable for field crops in eastern New York (Bd24-2a) and southern New York and northern New Jersey (Bd20-2b) are 53% and 71% covered by lights, respectively (Fig. 3-4). These soil types can be considered endangered since the physical alteration of the soil profile is substantial. The potential loss of entire soil mapping units, with their unique history of formation and biology, gives rise to the issue of the loss of biological diversity inherent in those soils.

Urban Occupation of Soils in the Four Top Ranked Agricultural States

To further examine trends in urbanization, we applied our analysis to California, Illinois, Florida, and Wisconsin, the states with the highest agricultural production in the United States (market value according to the U.S. Bureau of the Census 1987). Results are considerably less ambiguous than the continental view and show a disturbing, positive correlation between urban sprawl and the loss of productive agricultural soils. In these states, urban development appears to be taking place on the soil groups best suited to agriculture (Table 3-2).

California and Illinois perhaps best demonstrate this trend, with urban development occupying soils with the fewest FCC limitations to agriculture. In California, nearly 16% of the surface area of the best soil for agriculture is in urban use. In Illinois, 8.27% of the soils that have no limitations is lost to urban use. Almost 5% of the total land

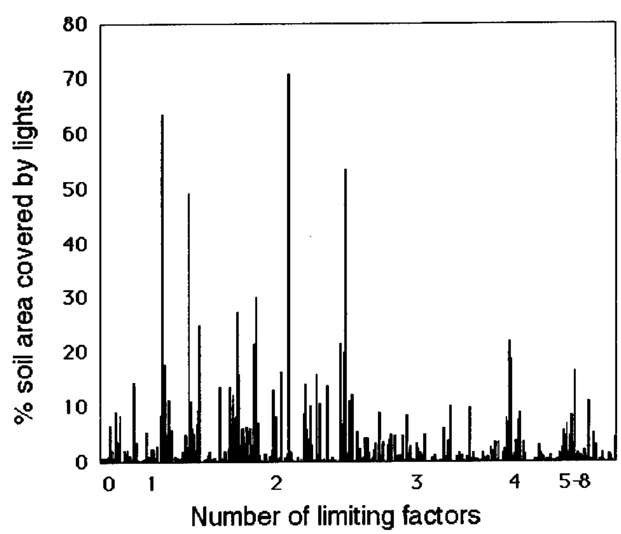

Fig. 3-4. Percent of soil area covered by lights for all 315 soil units for the United States. Soil units are from the United Nations Food and Agriculture Organization digital soil map of the world. The soil units are rated by using the Fertility Capability Classification system. Note that some soils are nearly completely covered by "city lights," indicating a high degree of urbanization.

Table 3-2. Results for soils (United Nations Food and Agriculture Organization) of four top producing agricultural states; soil units grouped and ranked by number of physical factors limiting agricultural production (light data from DMSP/OLS composite 89+% lit).

Number of limiting factors	1987 agricultural production ($ billions)[a]	Total area of soil class in state (km²)[b]	Soil area covered by lights (km²)	% soil area in state covered by lights	% urban area from 1990 census[c]
California	$12.71				
1		53,149	8,499	15.99	
2		39,619	3,510	8.86	
3		112,186	1,812	1.61	
4		57,451	1,630	2.84	
5		61,538	3,881	6.31	
8		80,627	788	0.98	
Totals		404,571	20,120	4.97	5.2 (21,176 km²)
Illinois	$4.97				
0		68,536	5,670	8.27	
1		66,479	1,960	2.95	
3		10,445	364	3.49	
Totals		145,460	7,994	5.50	5.5 (7,854 km²)
Wisconsin	$4.18				
0		23,648	481	2.03	
1		54,519	2,823	5.18	
2		18,390	125	0.68	
3		23,706	192	0.81	
4		23,064	87	0.38	
Totals		143,328	3,707	2.59	2.9 (4,086 km²)
Florida	$3.93				
1		8,780	617	7.03	
2		37,458	4,996	13.34	
3		80,789	7,368	9.12	
4		11,331	927	8.18	
Totals		138,358	13,908	10.05	9.5 (13,282 km²)

[a]Market value of agricultural products (1990 Census of Agriculture).
[b]Total areas do not include water bodies.
[c]From 1990 Census of Population and Housing, incorporated cities and towns with population greater than 2,500.

surface of California is in urban use, and 5.5% of the total land area in Illinois is urbanized. In both cases the percent of soil surface area in urban use drops substantially as the number of limiting factors increases.

In Wisconsin, however, the soil group having the most surface area in urban use is soils with one limiting factor, leaving the soils with zero limiting factors less developed. In the case of Wisconsin, this pattern may reflect preservation of the best of farmland and deserves further examination. If the "best" two soils in Wisconsin (those with zero and one limiting factors) are tallied together, though, then most of the development is clearly still on the best soils, leaving those with two or more limiting factors relatively undeveloped. According to our inventory, about 2.6% of the total surface area of Wisconsin is urbanized.

The pattern for Florida resembles that of Wisconsin, although the economic and social pressures at work there are extremely different. Even though Florida generates a considerable income from agricultural products (nearly $4 billion annually), the highly sought after living environment of its coastlines causes most of the urban development to occur there, where the soils are less suited to agriculture. This situation may give a false appearance of farmland preservation. Of the soil types with two or fewer limiting factors, Florida has lost 12.1% to urban use, while over 10% of the entire surface area of Florida is urbanized.

Long Term Impacts - Food Security and Conservation

At the continental scale the trend in land use conversion indicates that development is favoring the soils with fewer agricultural limiting factors. While preservation of the very best soils does seem to take place in some cases, it is occurring at the expense of the next best soils, which are often located nearby. This pattern is evident in the four

most economically important farm states, except that in some states the very best soils do not appear to be preserved at all (e.g., California). Our data tend to lend credence to the theory that development is associated with soil resources with higher production potential. Since many of the very same physical properties that make soils good for agriculture are also good for construction, the relationship is logical. Economic incentives, then, are negatively synergistic: "good" soils bring economic wealth, thereby encouraging development, but are also themselves attractive soils on which to build. Short-term economic forces may tend to undervalue agricultural use relative to urban development, especially when agricultural production can be economically shifted to distant areas due to inexpensive transportation. That the top four agricultural states are experiencing this trend, however, bodes ill for sustained productivity in the United States.

While the overall agricultural potential of the United States may not be seriously diminished at present, if the trend is allowed to continue, the country may soon experience a decline in agricultural production. Currently, there is less and less reliance on local agricultural products in the United States. Many grocery stores are stocked mainly with produce generated in a few primary agricultural zones in the United States and abroad. As the local soils are converted to nonagricultural uses, those localities will be even more reliant on their access to national or international markets. As such they will be vulnerable to changes in those markets and will be in direct competition with a very broad and, in some cases, wealthy customer base for the products. If the need arises to revitalize local agriculture to support growing populations nearby, only the poorer soils will be available for use. These soils will require more fertilizer and other inputs since more limiting factors will have to be overcome to make the soil produce a crop. The need to farm poorer soils will tend to increase the cost of production and the price of food. An example of this potential can be found in the state of Pennsylvania. Traditionally rich in farmlands, university experts estimate that Pennsylvania is losing 1% of its prime agricultural land to development each year, according to recent estimates (G.W. Petersen, Pennsylvania State University, personal communication). If the trend continues, in 100 years there will be no more prime agricultural land in the entire state. At that time, the human population will be much larger, suggesting that Pennsylvania will become increasingly dependent on outside agricultural resources.

In a future world of large human populations, where will those critically needed soil resources be found? Many countries are all depending upon the surplus production of the United States and other productive regions of the world to help carry their growing populations through the next 50 years. However, the United States, too, is depending on its current surplus capacity to feed its growing population. In fact, the U.S. agricultural production capability as it is now may be overcommitted by a factor of three by 2050 since a large percentage of the world's population expects that the surplus production will be available to them. Given this possibility, it would be prudent to protect the best agricultural soils from development. Not only should the best soils be protected, but it is vitally important that the farmland conservation effort take place at the local level and not simply at the national level. Consideration should be made for sustainable development at the local level, so that there is not the forced reliance of local populations on the interstate transportation systems that consume huge amounts of fossil fuels and are deteriorating under heavy use. While more detailed local analyses are needed to shed light on how each region of the country will be affected by the loss of soil resources, one certain outcome is that depletion of productive soil will bring with it a dependence on more distant resources and require ever higher yields per remaining acre on poorer soils.

Another concern brought out by this study is the potential loss of certain soil types or unique soil units to urbanization. Our results indicate that four soil types, as classified in the UNFAO system in the United States, may be in danger of disappearing under urban/suburban structures. Is the loss of "soil diversity" meaningful in a biological or economic sense? The study of soil biodiversity is a relatively new field, yet recent studies indicate that great diversity may exist in soils, with their unique physical structure, environment, and history of formation (Huston 1993). The loss of soil types may therefore represent loss of whole biological communities unique to that soil type. The conservation of soil diversity may bring into question the wisdom of converting to agriculture soils that have not previously been cultivated. Agriculture seriously disrupts the soil by changing its chemistry, structure, and ecological dynamics. Many of the soils that have already undergone agricultural transformation are in locations that (for the most part) limit soil loss to erosion and other adverse impacts (even so, soil erosion is an increasingly severe problem). As stable soils become unavailable to agriculture through conversion to urban/suburban infrastructure, soils less suited for cultivation may be used for farming. Farming such marginal soils could increase erosion resulting in the destruction of many soils, right down to the bedrock or parent material. This process has already occurred in many parts of the world such as the Caribbean Islands (Haiti) and areas in South and Central America, Asia, and Africa (Ehrlich 1997).

Conclusions

Our research demonstrates the use of nighttime images of the Earth, from the DMSP/OLS sensor, to measure the extent of urbanization and assess its impact on soil resources. Results show that urban development follows soil

resources and that, in general, the best soils are being converted to nonagricultural uses by urban sprawl. In addition, some distinct soil types, with their unique physical structure and history of formation, may be in danger of elimination, likely resulting in a substantial loss of belowground and aboveground biodiversity. The conservation of soil diversity is only now being discussed in scientific circles. With the increasing global demands on agricultural production, protection of the best agricultural soils emerges as an important priority, especially when considered from the viewpoint of future generations.

The paramount importance of soil resources suggests a need for a global assessment of urban sprawl and its effect on soil productivity. This assessment should include not only impacts on the soil resource but a more robust analysis of potential loss of global agricultural productivity. Such an analysis, using soil- and climate-based production models, will help develop forecasts for management, planning, and climate change research. Given the very real possibility of temporal and spatial displacement of climatic regimes under global change scenarios, it is critical that any future work include not only basic soil fertility characteristics but a realistic assessment of the impacts of climate change on agricultural systems.

Acknowledgments

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Chapter 4: Changing Patterns in the Number of Species in North American Floras

by

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Abstract. In this study we used data from published floras to produce contour maps of flora size and percentage of exotic species in North America for two specified unit areas (1,000 and 1,000,000 ha) and two specified years (1900 and 1996). Flora size decreases toward higher latitudes and is greatest in the southeastern United States. The number of species in floras decreases from east to west. This decrease may result from drier environments, which have been linked to reduced diversity, and to a less thoroughly documented flora. Increases in the size of floras since 1900 probably do not reflect increased plant biodiversity but rather suggest that plant life has been more thoroughly documented. The average size of floras in parts of the eastern United States has decreased since 1900, but this decrease may be a result of increased botanical interest in unusual, but relatively depauperate, environments. Proportions of exotic species are greatest in the northeastern United States. The west coast also has relatively higher proportions of exotic species. The proportion of exotic species is least in the mountain West and in the far northern latitudes of Canada and Alaska. Despite the lack of complete or consistent scientific data, we believe that floras represent a valuable data source to assess biodiversity.

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Introduction

Biodiversity and Exotic Species

In recent years, scientists, government officials, and the general public have become increasingly concerned over growing threats to biological diversity. Biological diversity—or biodiversity—represents the variation in life forms that exist on earth. This variation occurs at every level of the taxonomic hierarchy, but most discussion of biodiversity focuses on species diversity. Every species on earth plays a unique role in maintaining and balancing ecosystem processes and functions. The high level of interdependence of species in ecosystems suggests that a reduction of biodiversity at any taxonomic level could produce undesirable results. For example, virtually all animal life depends directly on the food energy trapped by plants through photosynthesis. However, plant life also depends on other organisms, such as microorganisms and small animals (macroinvertebrates) that return to the soil the nutrients that plants need. Similarly, plants often depend on insects or birds for pollination and dispersal. Reduced biodiversity of any of these groups would certainly affect the other groups (Wilson 1988).

Human life is also bound to the diversity of plants and animals (as well as other types of organisms such as fungi and bacteria). Although all groups of living organisms are vitally important to humans, we focus here on plants. Plants provide not only food energy but also a host of other products, such as rubber, fiber, medicines, and fuel. In recent years, plants have yielded valuable drugs to treat malaria, heart disease, various cancers, and other ailments, yet only a tiny fraction of the world's plant species has been studied in detail. Pharmacologists believe many thousands of other useful medications remain undiscovered in the world's plants. Plants are also vital to maintaining and improving the overall health and function of the world's ecological systems. These "ecosystem services" include regulation of rainfall and runoff, erosion control, flood prevention, climatic moderation, and a host of other functions whose value cannot be measured.

Thus, threats to biodiversity represent a threat to many of the tangible and intangible benefits that other species provide to humans. Much of the attention on biodiversity has focused on tropical rain forests, which have the greatest species diversity of any place on earth. According to United Nations estimates, however, the United States is also one of the richest countries in the world in terms of its biodiversity, ranking eighth in the world in the number of plant species (Groombridge 1992).

Patterns of Species Diversity

For many years, scientists have been trying to understand differences in species diversity in different places and at different times. We know that species diversity tends to be high in tropical areas, and that it diminishes toward the poles. We know that diversity tends to decrease at higher elevations. Moister climates tend to support more species than drier climates. Areas of greater topographic or environmental variability tend to have more species than more uniform areas (Ricklefs and Schluter 1993; Huston 1994; Rosenzweig 1995).

One of the most important trends in biodiversity is the increase in the number of species as the land area increases. Botanists call this trend the species–area relationship, and it is one of the most dependable rules in biology (Connor and McCoy 1979). Simply stated, large areas have more species than small areas. As a rule of thumb, the number of species approximately doubles when the land area is doubled five times (which is the same as multiplying the area by 32).

Species diversity can also change over time, and since their arrival, humans have profoundly influenced plant life throughout North America (Crosby 1986). Obviously, a corn field or a parking lot has fewer species than a prairie or forest. On a broad scale, humans have caused the decline, and even extinction, of many species. Thus, we might expect to find lower biodiversity in areas where human land-use is most intense.

Many human activities such as construction, urban development, and agriculture influence species directly by disrupting their habitat, by removing other organisms upon which they may depend, or by injuring or killing them. Less direct, but in many cases equally as disruptive to the native species of an area, is the introduction of exotic species.

Exotic Species: The Good, the Bad, and the Ugly

Exotic species are species that live and reproduce in places where they previously did not occur. The spread of exotic species may occur by natural means, but usually exotic species are spread by humans, either intentionally or unintentionally. Humans introduce exotic plant species for many reasons. Exotic species have been planted as ornamentals, for food crops, and for wind breaks and erosion control. In many cases, humans have spread exotic species unwittingly, for example as weeds associated with grain or livestock.

Humans have introduced exotic species to every part of the world. Some exotic species have become a common element of the local biota without causing major ecological consequences. But in many cases, exotic species have threatened the native biota, disrupted ecosystem function, and even wiped out entire populations of native species (Drake et al. 1989).

The Good

Many of our common agricultural crops, because they originated from areas outside the United States, are exotic species. Wheat (*Triticum*) and apples (*Malus*) from the

Middle East, rice (*Oryza*) from Asia, and tomatoes (*Lycopersicon*) from Central America are only a few examples of crop plants introduced to North America from other parts of the world (Harlan 1976).

The Bad

Unfortunately, many exotic species have had detrimental effects for both humans and ecosystems worldwide. In parts of the United States, exotic plant species threaten the survival of native species and disrupt ecological processes at multiple levels. For example, the tamarisk (*Tamarix*), introduced from Asia for erosion control, has become so successful that it has reduced the flow of many rivers in the West, disrupting water supplies and upsetting habitat for many aquatic animals. Aggressive exotic plants may also outcompete native plant species. The Chinese tallowtree (*Sapium sebiferum*) is rapidly taking over many of the native ecosystems in southeastern Texas, and exotic grass species—many resistant to grazing—have almost entirely replaced formerly dominant native species in California grasslands.

The Ugly

Still other exotic plant species not only disrupt the local ecology but also act as pests, nuisances, and eyesores. Kudzu (*Pueraria lobata*), introduced as ground cover in the southeastern United States, spreads rapidly in full sunlight to form a nearly continuous blanket of foliage over the ground layer and trees (Fig. 4-1). The vines choke out other plants, leaving a large area of barren and grotesque trailing sticks when they lose their leaves in the winter.

Botanists know a great deal about these and some other exotic plant species. In many cases, the spread of exotic species is closely related to changes in land use. Many common lawn and garden weeds, such as dandelion (*Taraxacum*), white clover (*Trifolium repens*), English plantain (*Plantago lanceolata*), and timothy grass (*Phleum pratense*), were introduced from Europe, and their growth is favored over native species by the agricultural practices that Europeans brought to North America.

Objectives

In this report, we have used information gathered by botanists over the past two centuries to assess general patterns of plant species diversity in North America and to show how these patterns have changed over time. Furthermore, we have tried to assess patterns in the prevalence of exotic species (i.e., species that originated outside North America) and to find out where and to what degree they have become more or less prevalent over time.

Our analysis focuses on the number of plant species and the proportion of exotic species at two different spatial scales and at two different points in time for North America. We include estimates for areas covering 1,000,000 ha and areas of 1,000 ha. For perspective, 1,000 ha equals 3.86 mi^2, and 1,000,000 ha equals 3,861 mi^2. For each area size, we estimate values for the years 1900 and 1996. Thus, our

Fig. 4-1. A field dominated by kudzu (*Pueraria lobata*) in northern Georgia. Kudzu, an exotic species native to Japan, was once planted widely for erosion control, but it has become an eyesore and a pest over large areas of the southeastern United States.

analysis results in four maps of North America for the size of the flora and four maps for the proportion of exotic species.

Because our analysis is continuing, and because we must rely on information collected by hundreds of different scientists over more than 200 years, the results are somewhat speculative.

Methods

Botanists have been collecting data on the distribution of plants in North America for centuries. Surprisingly, however, we still have much to learn about geographical variations in plant biodiversity and how it has changed over time. Information has been compiled and summarized in many different ways, including plant distribution maps, lists of herbarium specimens, and floras. In this report, we used a large collection of floras.

Sources of Data

A *flora* is a list of plant species that are known to occur within a region of interest. Often, the list is accompanied by a scientific description of each species that would permit it to be identified. Botanists have written floras for every type of region imaginable: city, state, and national parks, counties and states, a single pond or rock outcrop, and even for an entire country. Thus, floras span a wide range of land areas, from 1 ha or less to many millions of hectares. Equally varied are the reasons for writing a flora; these reasons include assisting in environmental impact assessment, determining conservation value of a potential nature reserve or park, and simply preparing an authoritative guide to the plant species of a region.

Despite the varied types and purposes of floras, we believe they offer great potential for research. Our study represents the first attempt to glean information from thousands of floras spanning the entire continent of North America.

We used many different strategies to acquire the floras used in this study. We searched university and government libraries, used computerized index searches, scanned more than 30 key botanical journals, read the bibliography and reference lists of botanical surveys and floras, used government document searches, corresponded with other botanists, and even posted e-mail requests on relevant bulletin boards. Still, we are constantly discovering new floras.

For each flora, we determined the total number of plant species and the number of exotic species known to occur within the region covered by the flora. We then ascertained, from the flora itself or from other sources, the latitude, longitude, area, average elevation, and the range of elevations for the region covered by the flora. We also enumerated the number of plant families and genera, which we will analyze in future work. While the number of species in a defined region may be called that region's species richness, we prefer instead to call our data *flora size*, since the number of species listed depends not only on the number of species actually present but also on the accessibility of the region to botanists and to the history of botanical exploration. In many cases, the author did not specify which species were exotic, so we have begun to determine that ourselves. In this analysis, we used 1,343 floras with data on flora size and 547 floras with data on exotic species (Fig. 4-2).

Methods of Estimation

Linear regression is a numerical technique used by statisticians and scientists to study relationships between different phenomena. For example, political pollsters use regression techniques to develop relationships between the way people vote and their income, education, and residence location. They then use this information to produce polling results and ultimately to predict the outcome of political races.

Similarly, we used the relationships between the number of plant species in published floras and some of the characteristics of the areas for which the floras were compiled to estimate the size of the flora for different locations and different times. These characteristics include the area, latitude, longitude, and elevation of the region; the year the flora was compiled; and a measure of the time and effort expended by the author(s) on botanical exploration. We developed mathematical relationships between these characteristics of an area and the size of its flora, and used those relationships to produce the flora maps presented herein.

Contour Mapping

We used contour maps to illustrate geographic patterns in flora size and proportion of exotic species in North America for two area sizes at two different times. A contour

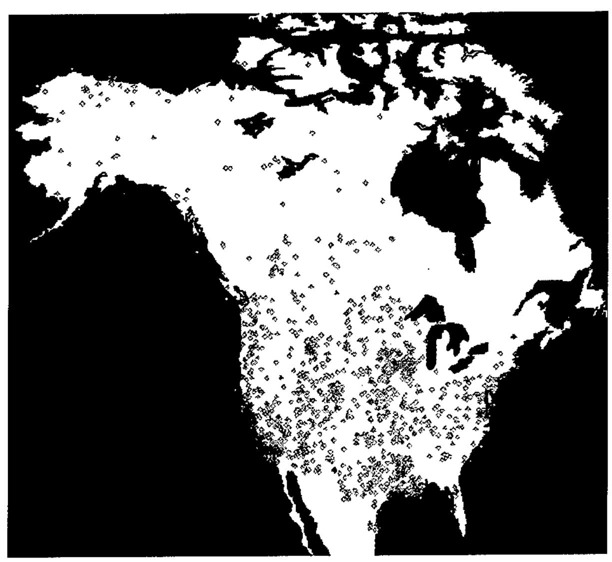

Fig. 4-2. Locations of floras used in this study. Points are centered on the geographic midpoint of each flora.

map is used to display geographic patterns of numerical data. The contour lines connect points of equal value, such that two locations lying along the same line have the same value. The *contour interval* represents the difference in value between adjacent contour lines. Notice that the value for places located between contour lines can only be estimated as some value intermediate between the values of the two contour lines. Regions between contour lines can be shaded using different colors to accentuate the variation. Weather maps commonly use such color schemes to show regions with similar temperatures and rainfall. The placement of contour lines on a map is based on data at known, or estimated, points. Mathematical relationships, in some cases related to regression lines, are used to further estimate values for locations between known points. Generally, accuracy improves as the number of data points increases. Accuracy is relatively high for areas on the map with a high concentration of data points and low where data points are more sparsely distributed (see Fig. 4-2).

Sources of Error

Although floras hold great promise for biodiversity research, they do have characteristics that may present limitations (Miller and Wiegert 1989; Mayr 1992; Palmer 1995; Palmer et al. 1995). Perhaps most important, no flora is 100% complete. There are almost certainly plants living in any given area that have not been identified and described. In addition, comparisons of floras are difficult because some are more complete than others. Floras have been compiled by thousands of different researchers who all used different methods and who worked to different standards. Some floras were written over many years by professional botanists who spent a lifetime studying one particular region; others were written after only 1 year or a few years of study.

Floras also differ greatly in the area covered, from less than 1 ha to millions of hectares. This variety creates difficulties in interpreting differences in diversity, although we have attempted to control for this problem statistically. In the same way, different regions have had different levels of botanical exploration (Fig. 4-2).

Other shortcomings of floras include inconsistency in reporting, imprecise definition of study area or collection methods, inconsistency in the definitions of species, and the use of different nomenclature (Kartesz 1994). Thus, variation in reported numbers of species may represent differences in definition rather than differences in biological variability. However, we suspect such problems related to synonymy are relatively minor.

Additional sources of uncertainty in these maps include the following:

1. The regression equations used to estimate diversity of a given region produce erroneous estimates when there are extreme values or some range of values with few observations. In such cases, the few observations have undue influence on the resulting regression equation, although the majority of observations may not behave in the same way.
2. Contour mapping is based on further estimating the value of the mapped phenomenon between known points. Errors are greatest where known data points are sparsely distributed. In addition, errors arise when the mapped value has great variation, since in that case it is more difficult to estimate values for locations between known values.

Despite these shortcomings, we believe floras represent one of the most comprehensive sources of data for plant biodiversity. With due consideration of these limitations and reasonable caution in assessing the accuracy of the results, we believe they provide useful information that is otherwise unavailable.

Results: Patterns of Plant Species Diversity in North America

Size of Flora for 1,000,000 Ha: 1900 and 1996

We estimated the size of the flora for areas of 1,000,000 ha for both 1900 and 1996 (Fig. 4-3). As is common for almost all groups of organisms, diversity decreases at higher latitudes. Biologists call this the latitudinal gradient in species diversity. Diversity reaches a maximum in the southeastern United States, which is well known by botanists for its high biodiversity (White and Miller 1988). This rich biodiversity may be due at least in part to the warm, moist climate and relatively mild winters, which are commonly linked to biodiversity. The marked variation in habitat types over moderately sized areas in the southern Appalachians also contributes to this high diversity. Size of flora decreases toward the west and north. Westward decreases may be related to the increasingly dry climate, less environmental variation, and the relatively shorter history of exploration. With its long settlement history, the flora of eastern North America is more comprehensively known than that of the West.

Note that the size of the flora has increased in 1996 relative to 1900, especially in the mountain West. The increase in size of flora over time is probably not due to biology alone. Development in the West has provided increased accessibility, and the flora has probably become more thoroughly described throughout the continent since the turn of the century. Nevertheless, greater diversity in the Rocky Mountain region compared to the surrounding areas is probably real and may be attributed to the wide range of elevation, and thus the high diversity of potential environments, in this mountainous region.

Size of Flora for 1,000 Ha: 1900 and 1996

The flora size for areas of 1,000 ha for both time periods is much smaller than for the 1,000,000-ha scale, simply reflecting a smaller area (Fig. 4-3). The decrease in diversity from east to west remains, although the peak in the

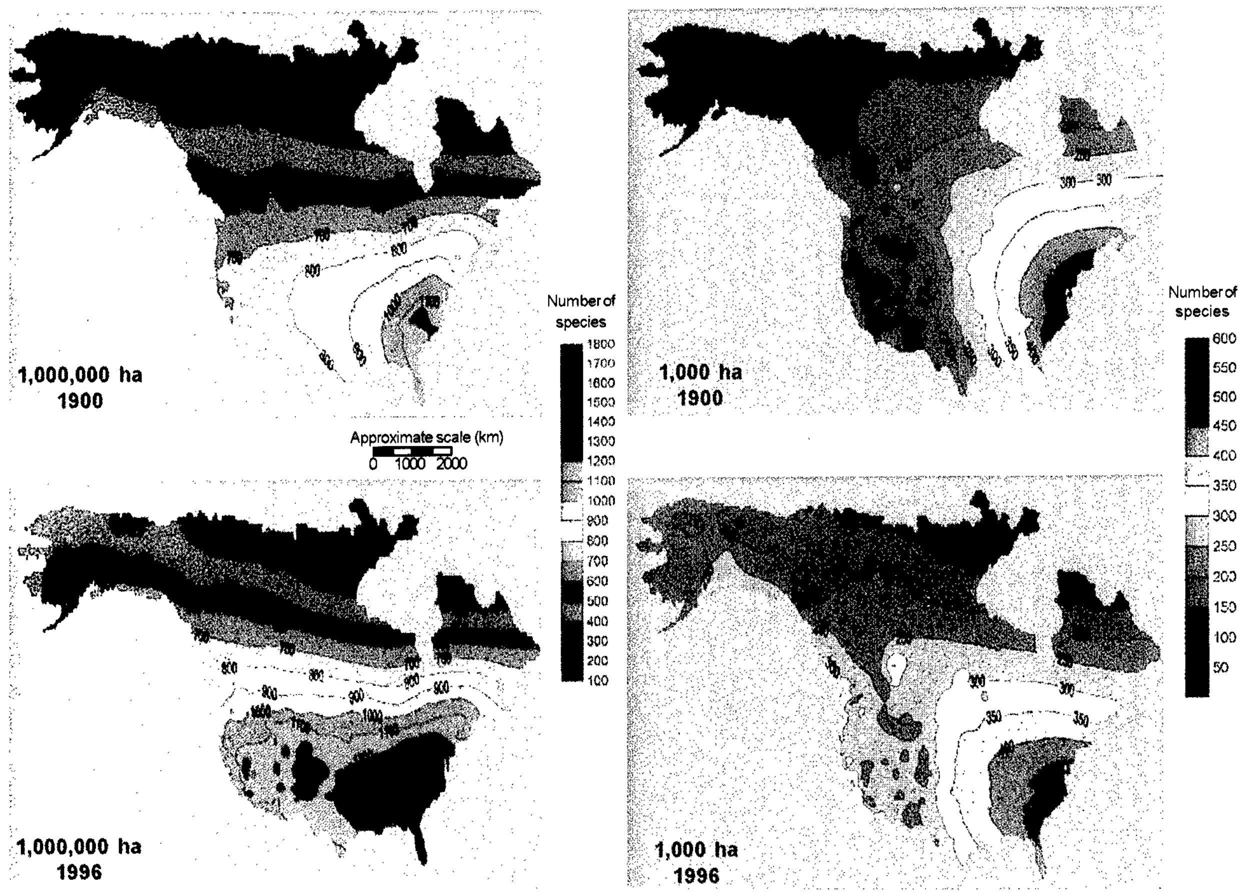

Fig. 4-3. Estimated size of the flora for areas of 1,000 and 1,000,000 ha in 1900 and 1996. The maps can be interpreted by considering any point on the map as the center of an area of the specified size. An area of 1,000,000 ha is equivalent to the area enclosed by a circle with a diameter of about 70 mi; 1,000 ha is equivalent to the area enclosed by a circle with a diameter of slightly more than 1 mi.

Southeast is less pronounced. In addition, the latitudinal gradient is reduced. The slightly enhanced diversity in Alaska may reflect the relatively high diversity of some coastal, temperate rainforest environments. These environments harbored many species adapted to cool climates when glaciers covered much of the interior during Pleistocene ice ages.

Notice too the "trough" of reduced diversity along the Rocky Mountain backbone, in contrast to the "ridge" of enhanced diversity for the floras covering areas of 1,000,000 ha. These patterns are not necessarily contradictory. For smaller areas, the size of the flora is reduced, perhaps due to the well-known trend of lower biodiversity with increasing elevation (Huston 1994). But larger areas contain a wide range of environments, such as mountain slopes, valleys, canyons, and the like. The wide variety of different environments in mountainous terrain may therefore support a larger number of different plant species adapted to the many different environments present, although the number of species within each environment may be smaller than similar-sized areas in lowlands. The different geographic patterns at different spatial scales suggests that the species–area relationship varies significantly from place to place.

From 1900 to 1996, flora size increased for much of the West but decreased in parts of the East. The increase in the West probably reflects increased knowledge and better documentation of the floras. The possibility that floras are decreasing in size in eastern North America is troubling and could possibly be a result of continued human population growth, development, and urban encroachment. However, we believe it is more likely that the flora size has decreased in the East due to growing interest among botanists in preparing floras for very unique environments such as rock outcrops, bogs, and ponds. Although these environments often house rare and unique species, they are typically depauperate; that is, they harbor relatively few species. Thus, increased focus on these special environments would lead to lower average flora size for small areas, but not, as observed above, for larger areas, which

already incorporate these special habitats. More data from floras in the East are needed to better understand this pattern.

Proportion of Exotic Species in 1,000,000 Ha: 1900 and 1996

We determined the proportion (in percent) of the flora that consists of exotic species for an area of 1,000,000 ha in 1900 and 1996 (Fig.4-4). The resulting maps show the proportion of exotic species. For a region covering 1,000,000 ha, the proportion of exotic species is greatest in the mid-Atlantic region and New England. This high percentage of exotic species probably reflects the very high human population density, the intensity of development and disturbance, and the long history of European settlement there. The proportion of exotic species also increases near the Pacific Coast, probably due to proximity to settlement and development and a long history of European settlement, initially by the Spanish. The proportion of exotic species near both coasts has increased since 1900. The spread of exotics from port cities is not surprising, because it is likely that seeds were inadvertently introduced in ballast, packing materials, and soil arriving on ships at these ports.

There is a pronounced minimum of exotic species toward the middle of the continent, reflecting the shorter development history and greater isolation, which would tend to lower the probability of invasion by exotic species. In 1996, however, there appears to be a trend of increasing exotic species bulging northward from Mexico and the Caribbean into the southern plains. There is also a pronounced latitudinal gradient in proportion of exotic species. There are three possible reasons why fewer exotic species occur in the northern latitudes: (1) relatively few exotic species can survive the extreme cold, (2) most species adapted to extreme cold already occur throughout the Arctic, and (3) there has been relatively little human influence because human population density is low and consequently landscapes are relatively undisturbed.

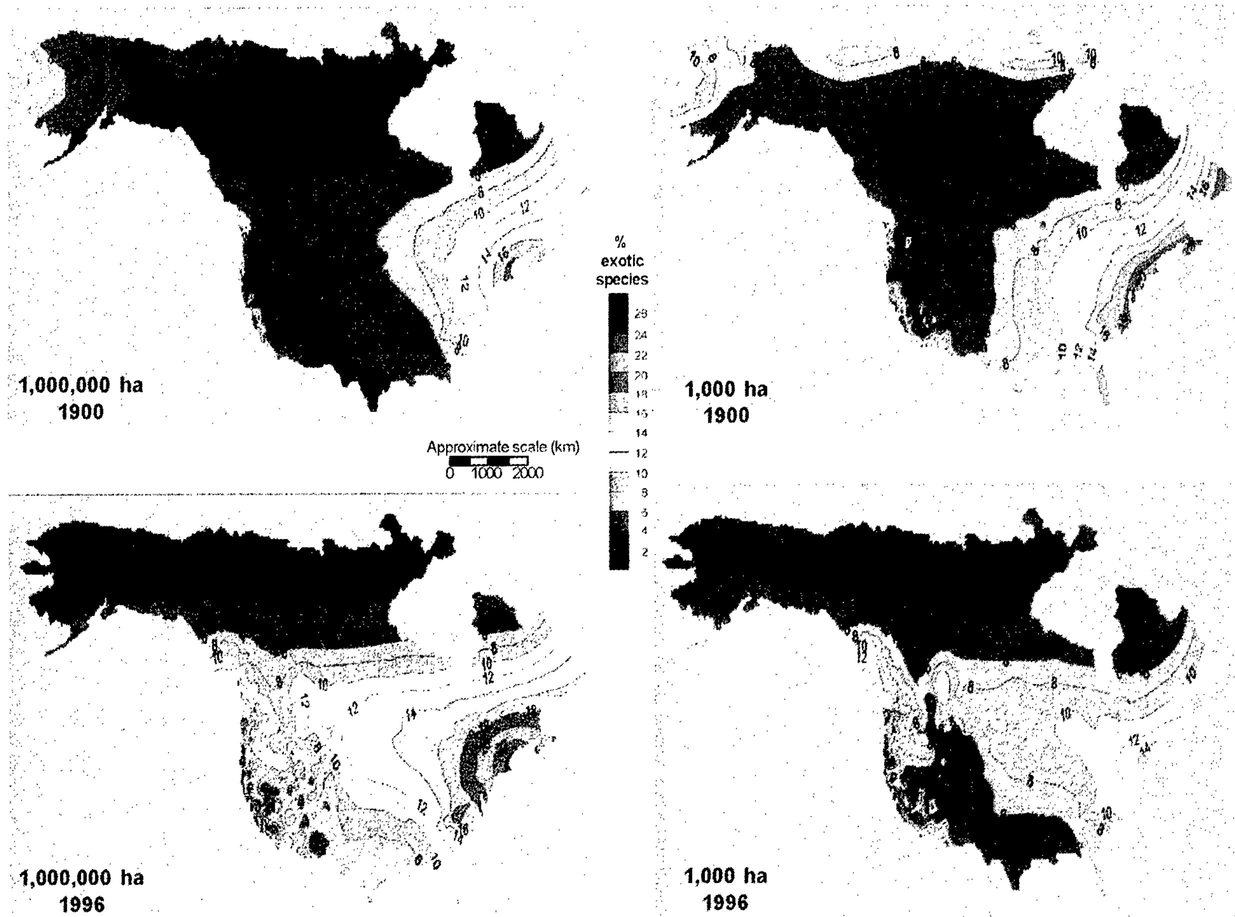

Fig. 4-4. Estimated proportion (percentage) of the flora consisting of exotic species for areas of 1,000 and 1,000,000 ha in 1900 and 1996. The maps can be interpreted by considering any point on the map as the center of an area of the specified size. An area of 1,000,000 ha is equivalent to the area enclosed by a circle with a diameter of about 70 mi; 1,000 ha is equivalent to the area enclosed by a circle with a diameter of slightly more than 1 mi.

Proportion of Exotic Species in 1,000 Ha: 1900 and 1996

The same patterns noted for 1,000,000 ha appear to hold for the smaller 1,000-ha area (Fig. 4-4), although the values are much higher for the smaller areas. This increase occurs because many exotic species are widespread and tend to occur repeatedly in numerous floras. Although exotic species proportions appear to be increasing in most places, the proportion of exotics in 1,000 ha appears to be declining in the Southeast. This finding probably reflects botanists' increasing tendency to seek out undisturbed, intact natural areas, preserves, and unique habitats for floral investigation. These intact habitats typically support few exotic species, and their increased representation among floras would lead to a reduction in the average level of exotic species.

Summary and Conclusions

In this project we have demonstrated the potential value of using the data contained in floras to study geographical patterns of plant species diversity and frequency of exotic species. Despite their limitations, floras contain valuable and comprehensive information on the plant life of North America that may not exist elsewhere. Moreover, by tracing floristic data collection through history, we can ascertain long-term trends and changes in these patterns over time. Our results are consistent with many previously identified trends in diversity (Ricklefs and Schluter 1993; Huston 1994; Rosenzweig 1995). Flora size increases as the size of the study area increases. Diversity decreases toward higher latitudes, especially over larger study areas. Flora size in North America is greatest in the southeastern United States. The high diversity may be related to the region's warm, humid climate, which is thought to be favorable for plant growth (Currie and Paquin 1987). Flora size in North America decreases toward the west, and this decrease may reflect, in part, drier environments as well as a less comprehensively documented flora.

By investigating floras compiled over a long period of time, we can assess changes over time in the size of a flora and the percentage of exotic species and relate these changes to historical patterns of land use. Increases in the size of floras since 1900 probably do not reflect increased plant biodiversity but rather mirror settlement patterns and land-use changes. As the West has been more thoroughly settled over the past 100 years, the plant life has been more thoroughly documented and the size of floras has therefore increased. The reason for the decreased size of floras in the eastern United States since 1900 is unclear, but it may be a result of increased botanical interest in unusual environments that house relatively few, but unique, plant species. Repeated inventory of plants in areas that were previously studied intensively may shed an interesting light on this question.

The patterns of exotic species distributions appear more directly and more profoundly linked to land use and land-use history. Proportions of exotic species are greatest in the northeastern United States and the Atlantic coast of Canada, which have the longest continuous history of European settlement and the highest population density in North America. The west coast also has relatively high proportions of exotic species, and it too has a long history of development dating to the eighteenth century, a large population, and intensive development over large areas. It is noteworthy that both of these regions are home to North America's largest ports and that both coasts have served as a gateway to tens of millions of human immigrants. Undoubtedly, along with the humans came many species of exotic plants.

The proportion of exotic species is lowest in the mountain West and in the far northern latitudes of Canada and Alaska, which are sparsely populated, minimally developed, and relatively isolated from sources of exotic species. Moreover, these cold, harsh environments require special adaptations that few exotic species have acquired.

This project, though preliminary in nature, has revealed distinct insight into the geographic variation in plant species diversity and the prevalence of exotic species in North America. Collection of additional data from floras in areas that are poorly represented at present (Fig. 4-2) will lend greater reliability and may shed additional light on the patterns discussed here. The resulting understanding of trends in the geographical distribution of biological diversity will be essential in developing strategies to best conserve it and to benefit from it.

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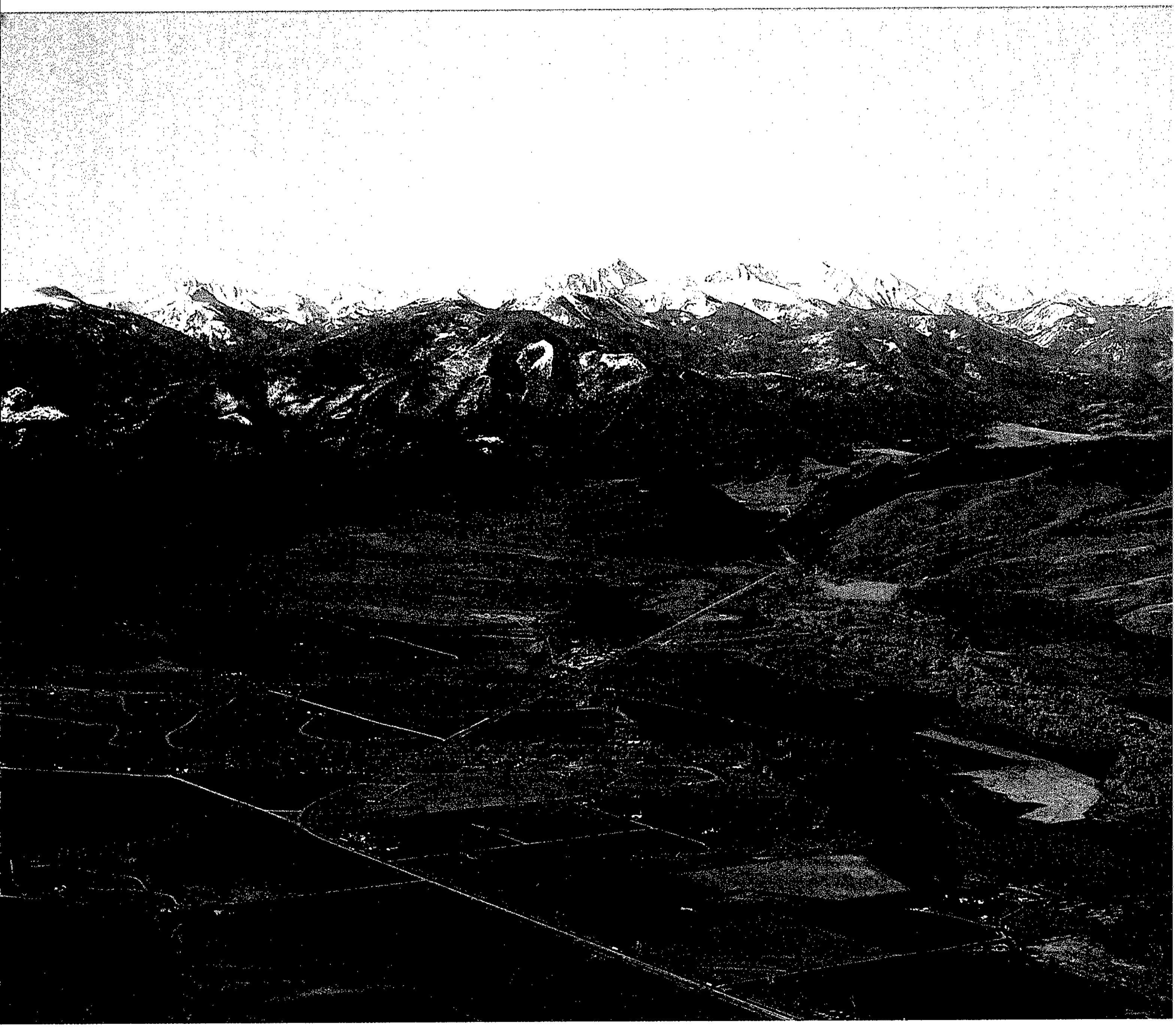
PART 2:
Regional Case Studies



Chapter 5: The Baltimore-Washington Regional Collaboratory Land-Use History Research Program

by

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Abstract. Land-use history studies in the Baltimore-Washington region provide the framework for a variety of environmental studies and regional partnerships. Multiple Federal and local agencies cooperated on a 200-year urban growth study in the Chesapeake region that led to the creation of the Baltimore-Washington Regional Collaboratory. Understanding of the contemporary landscapes is being sought through investigations of land-use and landcover dynamics using the technologies of geographic information systems (GIS), remote sensing, and environmental modeling. Data are being collected by many local, State, and Federal groups and then processed and organized into a GIS and made available to the public through the Collaboratory's web site (http://www.umbc.edu/bwrdc). Results of the land-use history research have been presented in a video that was cited by Maryland's Governor Parris Glendening for influencing the legislature to promote the State's "Smart Growth" initiatives. A series of follow-on activities resulting from the success of the Collaboratory's land-use history research efforts includes the National Science Foundation's Urban Long-Term Ecological Research site for Baltimore, a forest fragmentation study with the U.S. Forest Service, the urban-rural index with the Bureau of the Census, and cellular automaton model development. Land-use history has proven to be the catalyst for integrating and communicating the complex issues of linkages between physical, ecological, and social processes that compose the human ecosystem.

Program Description

Urbanization is now recognized as a ubiquitous phenomenon of global importance. As cities grow, they expand over agriculture, wetlands, wildlands, and forests, thereby changing the physical shape of the landscape as well as the functioning state of the ecosystem (Vitousek 1994). We are learning that these physical and ecological changes also may have profound impacts on shaping the social character of our cities, suburbs, and rural areas.

As the largest estuary in the United States, the Chesapeake Bay is well known for its ecological diversity and rich historical and economical significance to the nation. The Chesapeake Bay region has been mapped and studied since European settlement, and because of both its history and the records kept by government agencies and historians, a wealth of information is available to researchers. For the past 25 years, environmental research efforts have focused on tracking nonpoint source pollution and the processes involved with the bay's over-nutrification. Since the mid-1980's, with the tremendous urban and suburban growth that has occurred, large patches of vegetated land cover are rapidly disappearing. Techniques that will integrate the Chesapeake Bay region's wealth of data in order to support better decision making and improve land management policies and planning are necessary under the extensive pressures of urbanization and population growth. Collaboration bringing together data from scientists, researchers, local land managers, and decision makers is needed to effectively study these cumulative impacts on the bay's living resources and watershed.

The Baltimore-Washington Regional Collaboratory (the Collaboratory) is developing innovative ways to create user-friendly Internet web sites, useful map products, and advanced visualization tools to portray the dynamic nature of the region's historic land-use and landcover patterns and trends. The Collaboratory represents multiple partnerships between local groups and county, State, and Federal agencies to share spatial data. The scientific goals of this research program are:

1) to provide a clearinghouse from which citizens and scientists alike can obtain useful historic and current information for the Chesapeake region in the form of maps, satellite images, and field collection data,
2) to use these data for understanding the impacts of human activities in the past and projecting the trends of human impacts for the future, and
3) to study the processes for interactions among the social, physical, and ecological components of the region.

The mission of the Collaboratory is to demonstrate the feasibility and utility of providing scientifically valid data in an easily understandable format to the general public and decision makers. The data provided through the Collaboratory include historic, comprehensive, and detailed information that is compiled into a spatial framework with geographic information systems (GIS) technology. These data sets are part of a comprehensive research program sponsored by the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF) and aimed at both quantifying the geography and ecology of the Chesapeake Bay region and delivering this information via an Internet clearinghouse. The Collaboratory also seeks to apply these data to community outreach activities with citizens, scientists, and managers.

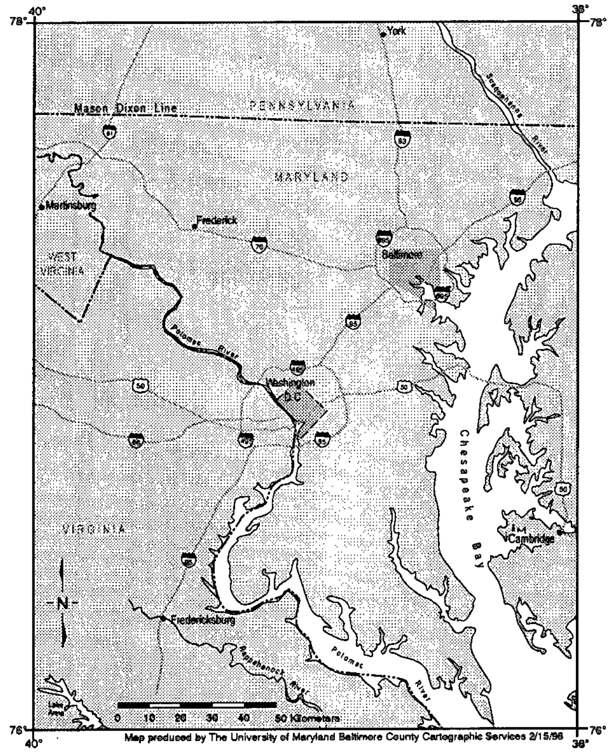

Fig. 5-1. Study area for the Baltimore-Washington Regional Collaboratory.

200 Years of Land-use History

As part of the Collaboratory's research program, the University of Maryland, Baltimore County (UMBC) in cooperation with NASA, the U.S. Census Bureau, and the U.S. Geological Survey (USGS) have been developing computer-based methods for collecting and integrating historic mapping and census records to study changes on the landscape over the past 200 years. The Collaboratory built a regional GIS as part of a cooperative study of human-induced land transformations. This study encompasses a 2 latitude by 2 longitude region (38 N 76 W to 40 N 78 W) focusing on the metropolitan areas of Baltimore, Maryland, and Washington, D.C. (Fig. 5-1). An interdisciplinary, multiple-agency team compiled information on principal transportation, urban development, hydrography, topography, and census data (Clark et al. 1996; Crawford et al. 1996). A USGS team had previously developed methodology for integrating these types of data for a study of the San Francisco Bay (Kirtland et al. 1994), and their methods were adapted to organize and spatially reference (in GIS format) the database for the entire Baltimore-Washington study region. Eight images were generated to portray the urban growth from 1792 to 1992 (Fig. 5-2). Urban land-use and transportation compilations were accomplished using manual map transcriptions, table digitizers, and, beginning with the 1972 data, digital image processing of satellite scenes. The criteria for defining urban areas was established as a population of 500 persons. Census information, obtained from historic census records, was correlated with historic maps to determine the locations and boundaries of each urban area. This information was then formatted, input to a GIS, and placed on the Collaboratory's web site (http://www.umbc.edu/bwrdc) for public access. From these eight images, we can recount the settlement patterns that transformed the mosaic of native deciduous forest to the familiar fragmented landscapes of today (Zipperer 1993).

After a century and a half of colonial development, urban patterns begin to show up around the ports of Annapolis, Baltimore, and Alexandria (Fig. 5-2). These ports represent the primary centers of trade and development. Colonial towns were often situated along the fall line, where ocean-going shipping ended and water power could be harnessed to run grain mills and basic manufacturing operations. By the mid-nineteenth century, Baltimore was the region's bustling urban and industrial center, with approximately 1 million people in the Baltimore-Washington

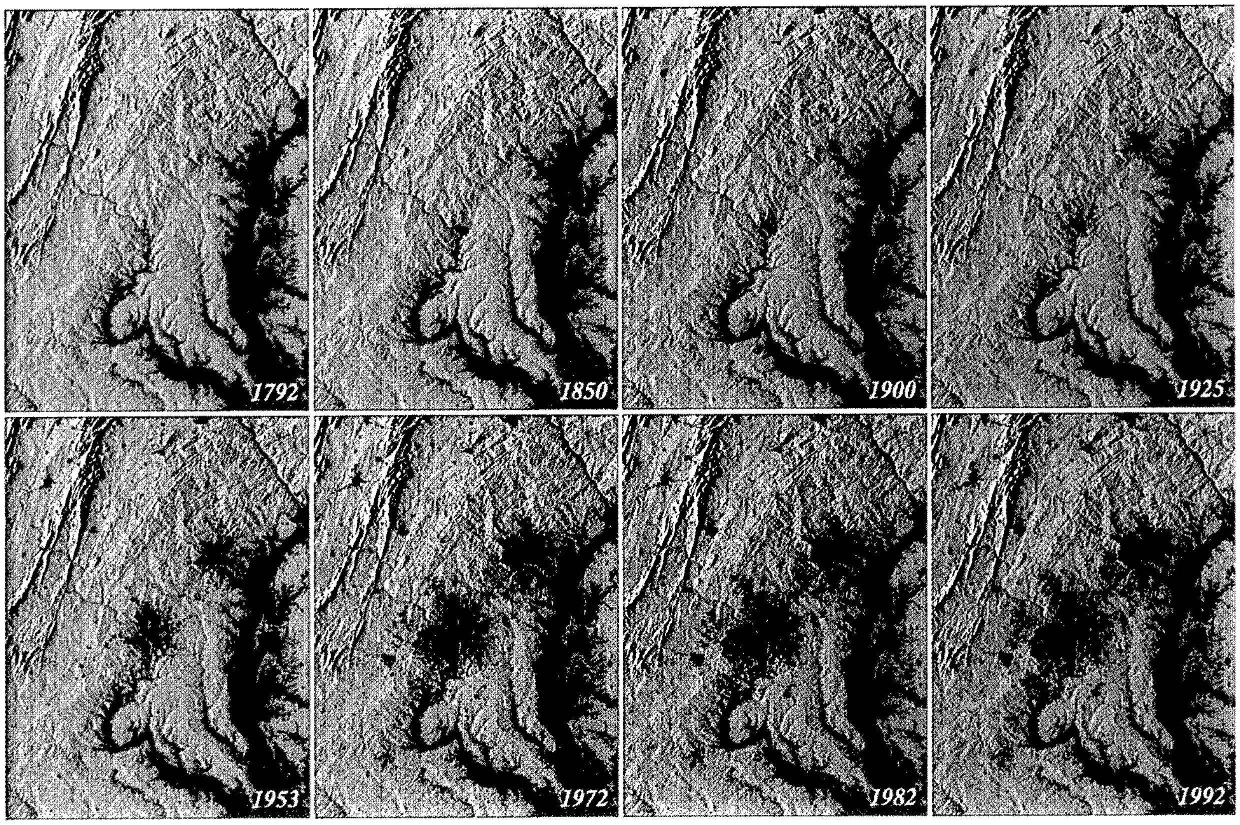

Fig. 5-2. Two hundred years of urban growth for the Baltimore-Washington region. Red pixels denote urban land use as defined by both the USGS and the Bureau of the Census.

region. A network of rural mill villages operated along the major tributaries of the Patapsco, Jones Falls, and Gwynns Falls valleys. Two million people began to form an expanded suburban environment at the turn of the twentieth century with the advent of street cars and rail line extensions. Lack of bridge infrastructure limited growth in northern Virginia and in the "corridor" between Baltimore and Washington. By the 1920's, the "inter-urban" rail infrastructure enabled commuter traffic to bring suburban village workers to the urban core of the cities. Corridors of urban growth seemed to follow these major commuter rail paths from both Baltimore and Washington. By the mid-twentieth century, the effects of growth could be easily seen, beginning with the Federal government's expansion during the 1930's and 1940's to the post-World War II population growth. Fertilizer use on lawns and agriculture was beginning to have a demonstrable impact on the bay's ecosystems during this period, and that impact was exacerbated by loss of more forest land. Automobiles, roads, and bridges significantly accelerated the expansion of the urban work force into the rural communities, creating the need for a suburban market infrastructure (i.e., the creation of towns for housing, food, and supply materials). Beginning in 1972 and expanding through the next two decades, urban land use filled in the Baltimore and Washington corridor, forming seeds for the megalopolis (Von Eckardt and Gottman 1964). By 1992, more than 8 million people lived in the study region. This fast-paced growth, combined with urban flight into the previously rural landscape, transformed the critical hydrologic buffers of forest and wetlands, causing increased sediment and pollution loading into the bay.

These historic perspectives for urbanization changes are helping citizens, scientists, and managers better understand the rates and true magnitude of these incremental, daily growth patterns. Eight images of urbanization over time for the study region (Fig. 5-2) were assembled into a video, a time-series animation that proved very useful to Maryland officials in their attempts to craft legislation to minimize the urban growth impacts (Masuoka et al. 1995; Masuoka et al. 1996). Governor Parris Glendening has credited this map visualization product developed by the Collaboratory team for winning legislative approval of his "Smart Growth" initiatives (Dobson 1997).

Visualization techniques and simulated landscapes are also helping scientists and citizens understand the complex effects of land-use management on land cover. The Collaboratory's regional GIS data can be applied to analyze more details regarding the growth stages in urbanization

impact studies. For example, vegetation ecologists are investigating how land-use processes influence landcover dynamics. Landsat satellite images of undisturbed deciduous forest canopy draped over the Baltimore terrain were used to portray predevelopment conditions (Masuoka et al. 1996; Fig. 5-3). The growth in urban land use was then overlaid as yellow boundaries to indicate where deforestation and agricultural lands have been displaced by urban activities. In the earlier perspectives, the port of Baltimore shows as the major urban center, along with the town of Westminster to the northwest, which was then an agricultural transshipment center. A century later, the expansion of market towns and transshipment centers is visible in the images, as are developing suburbs. Subsequent deforestation and overuse of agricultural fields resulted in heavy siltation, making many colonial-era ports inaccessible to shipping. The Baltimore and Ohio (B & O) Railroad line runs west from Baltimore, fostering growth in that direction. By 1925, "inter-urban" rail transportation had fostered the development of radial branches from the metropolitan center in a star-like pattern. Then, in just 25 more years, the population almost doubled, due to the defense-related industries of World War II, filling out the star branches connecting suburban areas to the central city over an improved transportation system. By 1972, suburban sprawl had filled in along the south-to-north transportation corridors. By 1992, the rampant growth of the 1980's and continued urban flight from both the central city and the older suburbs had transformed the region's once forested landscape into a single megalopolis connecting Baltimore and Washington to the south.

Scientists can use these historic GIS-formatted data layers to recreate and model the forest's capacity to intercept precipitation, filter atmospheric gases, cycle nitrogen, and support biodiversity (Foresman et al. 1996). Extensive field work using the techniques of paleoecologists, that is, sediment core analysis and analysis of historic records, is required to improve the scientific validity of the regional GIS data sets (Table 5-1). Through the work of paleoecologists, the Collaboratory is building a definitive picture of the land-use

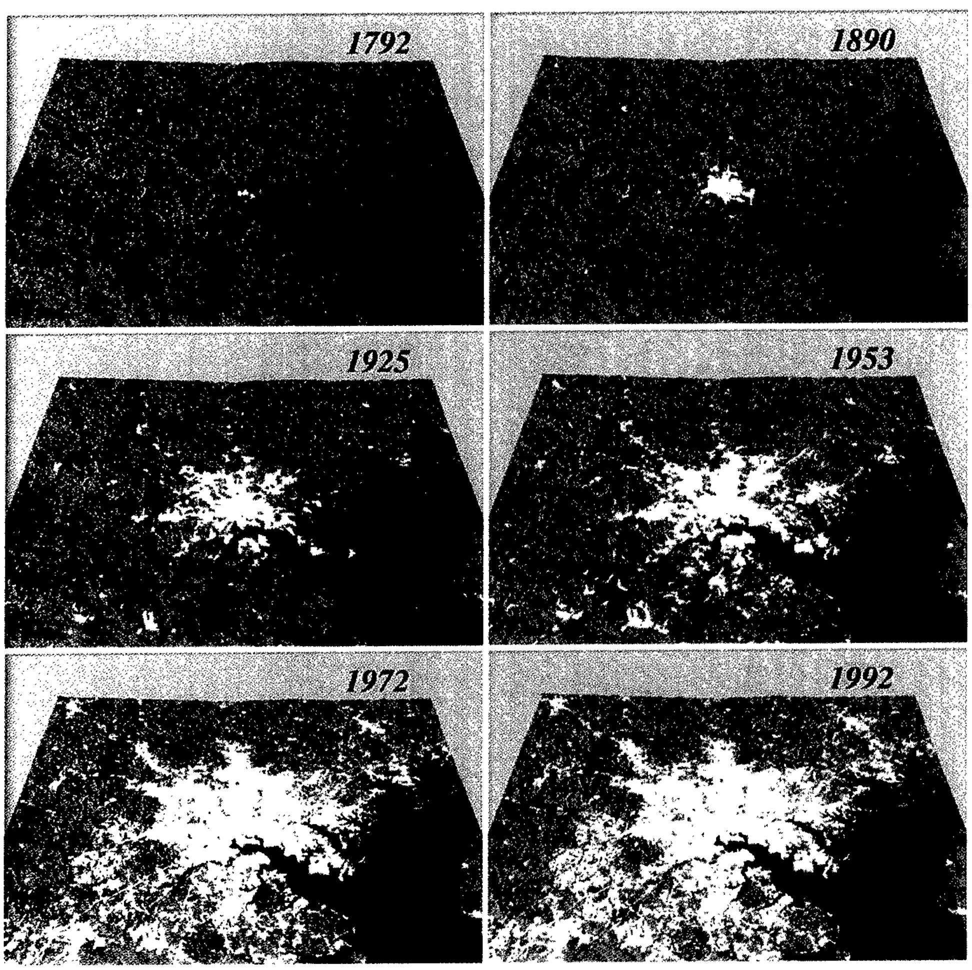

Fig. 5-3. Baltimore simulated forest land cover showing 200 years of urban growth in yellow.

Table 5-1. Historical trends of land use and land cover for the Chesapeake region (modified from Brush 1994).

Time Frame	Period	Land-use/landcover characterization
10,000 - 5,000 B.C	Pre-human	Boreal type forest succeeded by hemlock into enclosed canopy mixed conifers-deciduous forest
5,000 B.C.- A.D. 1600	Pre-European	Oak-hickory, closed canopy forest
1600-1800	Early settlement, colonial towns	20-40% land cleared for tobacco, grain, small farms, iron furnaces, and construction
1800-1900	Agrarian to industrial	60-80% land cleared for large farms, transition introduction of deep plough and guano-based fertilizers, metropolitan expansion
1900-25	Industrial urbanization	Chemical-based fertilizers, "inter-urban" rail feeding industrial suburbs
1925-50	Automotive urbanization	Increased fertilizers, large farm operations, wetlands drainage, suburban expansion
1950-75	Highway urbanization	Modern highway connections, drive-in commerce, mega-suburbs encroaching upon farmlands, wetlands, and forest
1975-90	Modern urban sprawl	Decrease in cultivated land and forest, urban expansion forms megalopolis

and landcover histories that characterize the Chesapeake region for the pre- and post-European settlement periods. The paleoecological records provide important clues to the effects of land clearing on sediment and nutrient loading rates for the Chesapeake Bay (Brush 1994). Land clearing had reached 20-30% by the time of the country's independence. Deforestation increased significantly due to both land clearing activities for tobacco and wheat farming and the fuel requirements for the numerous iron works that preceded the industrial revolution. By the end of the nineteenth century, 60-80% of the land had been cleared, and soil processes had been disrupted with the advent of deep plowing and fertilization practices; both were key factors in accelerating the bay's nutrification and siltation. The twentieth century has witnessed a significant reduction of ecological buffer systems for the bay with the loss of forest acreage, drainage of wetlands, and decrease in permeable surfaces. Quantifying these impacts with attention to the exact locations of past land-use management is a central part of the Collaboratory's research agenda.

Activities

The Baltimore-Washington Regional Collaboratory's land-use history research has led to a comprehensive research program in partnership with the U.S. Forest Service (USFS), Johns Hopkins University (JHU), the Institute of Ecosystem Studies (IES), and others. A brief description of these research activities will demonstrate the critical importance of improved understanding land-use history in assessing, predicting, and managing the nation's ecological resources, in the face of expanding human activities.

Long-Term Ecological Research Site

The National Science Foundation's Long-Term Ecological Research (LTER) program has awarded an Urban LTER grant for an interdisciplinary team of investigators housed on the UMBC campus. The Baltimore Urban LTER project is using the Collaboratory's regional data base as the foundation for long-term studies of the interactions or flux measurements between physical, ecological, and social systems along an urban-rural gradient within the Gwynns Falls

watershed (Fig. 5-4). An important feature of these research activities is the incorporation of educational links with area schools to involve students in the field collection and analysis activities, thereby offering enhancement to existing school curricula for math and the sciences. An example of these educational links is a partnership with local high schools to collect field data in forest patches that have been delineated by the UMBC scientists for validation and calibration of satellite sensors. Field data collection techniques have been developed and tested with high school educators and students in cooperation with foresters and ecologists from the USFS and Maryland Department of Natural Resources (DNR). The Collaboratory maintains a web site for access to the LTER research activities and data (http://baltimore.umbc.edu/lter).

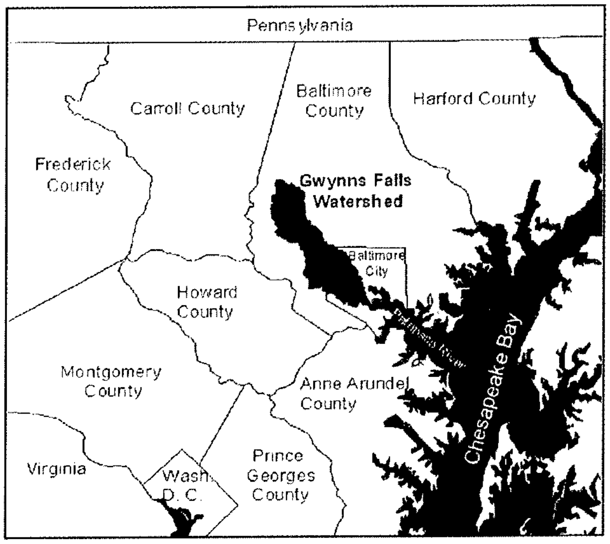

Fig. 5-4. Baltimore Long-term Ecological Research, Gwynns Falls watershed location map.

Multiple-Scale Analysis: Space and Time Considerations

The Collaboratory's research includes investigations into the application and validation of landcover characterization using remote sensing technology. The NASA Office of Mission to Planet Earth has sponsored the Collaboratory's research in assessing the spatial accuracy and best methods in applying remotely sensed data at resolutions ranging from 1 m to 1 km. Forest patch delineations are used to study the effectiveness of using different spatial resolutions (Fig. 5-5). These studies are important for determining which data and information systems (i.e., which sensors) are the most appropriate for different natural resource decision-making scenarios. Generally, finer resolution satellite data or aerial photography are used to characterize small areas on the ground, while coarser satellite data are used for entire regions. These investigations seek to provide qualitative results so that decision makers can more effectively choose from the suite of increasingly sophisticated data providers (i.e., NASA, other government agencies, and commercial vendors).

In addition to considering the spatial accuracy or appropriateness of remotely sensed data, the Collaboratory,

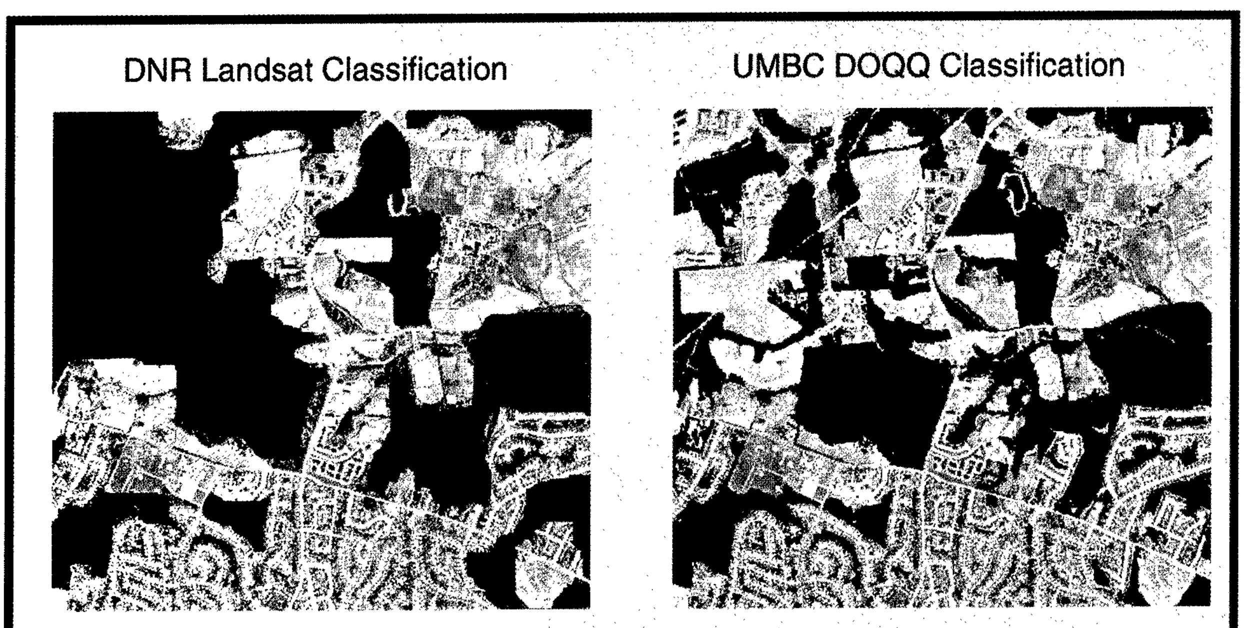

Fig. 5-5. Spatial analysis for forest patch map comparison for Landsat-derived classification (30-m resolution) versus digital ortho quarter quad classification (1-m resolution).

in collaboration with NASA Goddard Space Flight Center, is operating a satellite receiving station for the Advanced Very High Resolution Radiometer (AVHRR). This satellite-based sensor captures an average of four Earth images each day at 1-km resolution. These data have proven invaluable in monitoring greening and drought conditions of vegetation for broad areas (Tucker et al. 1985). Time series analysis also can be obtained by analyzing historical aerial photography for landcover changes. Figure 5-6 displays the shift in forest cover for a 22-year period on the UMBC campus. These methods use GIS technology to carefully register older photographs with current landcover images in order to precisely calculate shifts in forest, agriculture, and other landcover categories. National photography archives can provide aerial photographs for many parts of the nation going back to the 1930's and 1940's.

Historical Land Use and Population

Meticulous research into historical deeds, land records, zoning maps, and demographic or census records can provide important clues to the links between land-use and landcover dynamics. Using today's digital records, Collaboratory researchers are working at the level of individual land parcels for all of Maryland. As investigations become retrospective, the level of detail begins to diminish. However, a sufficient amount of information exists for the Chesapeake region to reconstruct large land holdings and correlate these land ownership records with census tabulations that begin in the seventeenth century. For national-level land use history studies, the county unit offers a fundamental organizing framework enabling county-level comparisons throughout the nation (Fig. 5-7 and see Chapter 2, this volume). The Collaboratory is conducting data collection activities at much finer resolution (i.e., parcel-level) for the counties surrounding Baltimore.

Land-use and population data are being investigated under two additional Collaboratory research projects. An urban-rural index (URI) is being created in cooperation with the U.S. Bureau of the Census to quantify the gradient from the inner city urban core to the rural extremes. Research on the URI is intended to provide a national index that defines levels along the gradient, thereby enabling quantitative comparisons for human impacts in areas of extreme environmental difference (e.g., desert versus tundra). Another research project is developing a cellular automaton model (a grid-based growth model) that will predict land-use futures under varying scenarios of transportation planning, population growth, and zoning. Over the past few years, cellular automata models have demonstrated great promise for assisting geographers and Earth scientists in understanding urban growth (Couclelis 1985; Clarke et al. 1997). All of these research activities will generate new information on land-use history for use by citizens, regional planners, and the scientific community.

Discussion

Improved understanding of land-use history provides the much needed perspective of examining past changes and trends in order to both comprehend and predict our future on the planet. Interagency cooperation, regional spatial data clearinghouses, and Internet-accessible information resources are important long-term investments to support generation of easily understood maps and information describing land-use changes and the effects of

Fig. 5-6. Temporal analysis of land cover using 1972 and 1994 photos of the University of Maryland, Baltimore County campus.

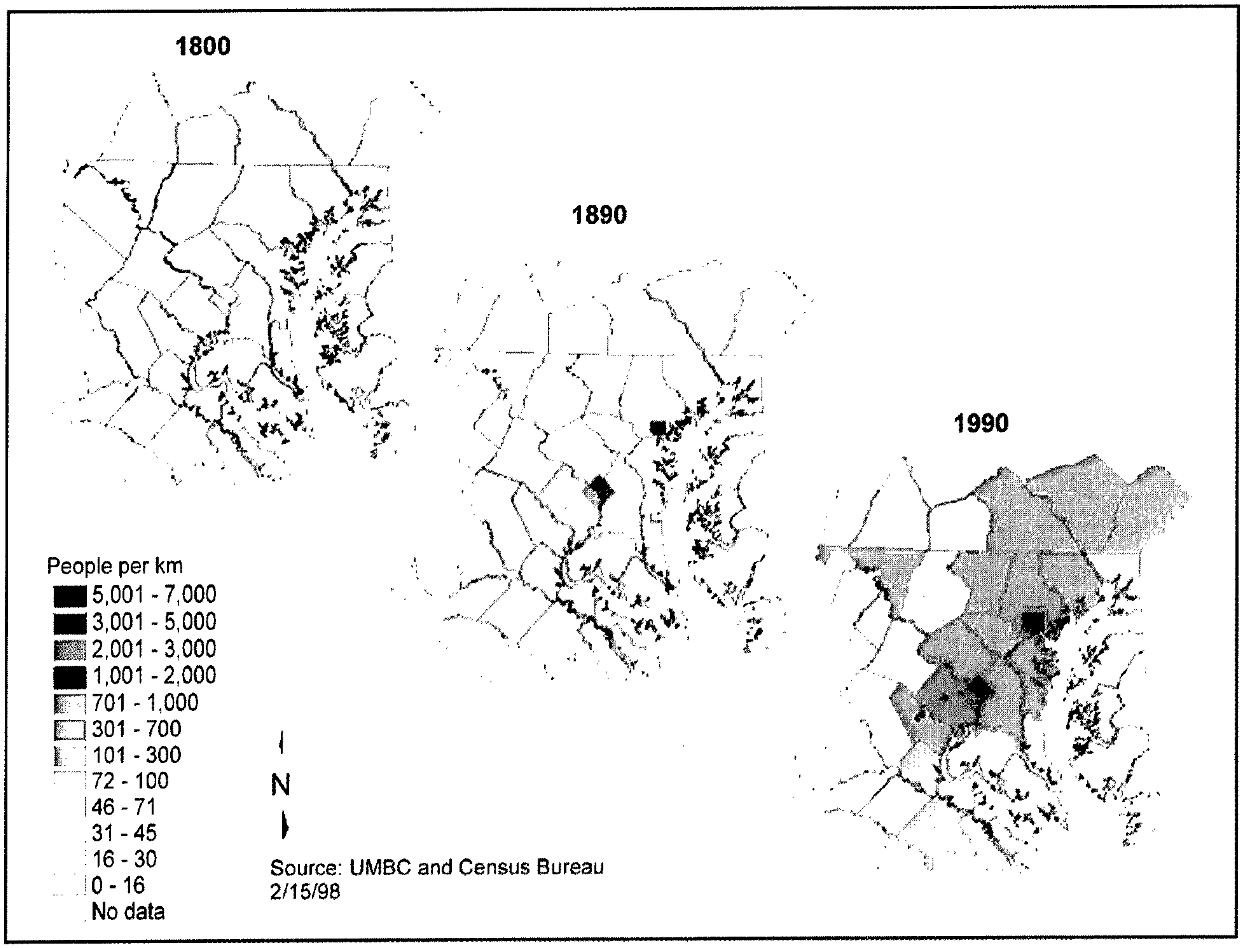

Fig. 5-7. Baltimore-Washington regional population density, by county, for 1800, 1890, and 1990.

human activities on the physical, ecological, and social components of human-dominated ecosystems.

Technological innovations for GIS, remote sensing, environmental modeling, and visual presentation methods offer credible scientific tools to harness the myriad land-use and landcover data and to make sense of these complex data for laypersons and scientists. Scientists can now begin to quantify the rates of change and magnitude of these changes for whole regions. At the same time, these tools promote the use of easily understood maps and visualization models to more effectively connect with the citizens and decision makers who control the day to day land management activities. State executives have adapted quickly to the use of these tools in leading Maryland towards improved growth management. As students become exposed to this information through the media and within school curricula, the next generation is being trained to address the many challenges associated with rampant population growth and patterns of urbanization. A quantitative approach is requisite for our struggle to identify key environmental problems, to predict the outcome of our current or planned development actions, and to restructure our natural resource management priorities to anticipate social, physical, and ecological consequences.

An improved understanding of land-use history establishes a foundation from which to interpret diverse data sets and foster cooperation in our quest to understand global land-use and landcover changes and to develop coping mechanisms to adapt to these changes. The focus of the LUHNA program is understanding the past and is the key for our journey to the future.

Acknowledgments

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Chapter 6: Historical Landcover Changes in the Great Lakes Region

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Abstract. Two different methods of reconstructing historical vegetation change, drawing on General Land Office (GLO) surveys and fossil pollen deposits, are demonstrated by using data from the Great Lakes region. Both types of data are incorporated into landscape-scale analyses and presented through geographic information systems. Results from the two methods reinforce each other and allow reconstructions of past landscapes at different time scales. Changes to forests of the Great Lakes region during the last 150 years were far greater than the changes recorded over the preceding 1,000 years. Over the last 150 years, the total amount of forested land in the Great Lakes region declined by over 40%, and much of the remaining forest was converted to early successional forest types as a result of extensive logging. These results demonstrate the utility of using GLO survey data in conjunction with other data sources to reconstruct a generalized "presettlement" condition and assess changes in landcover.

Introduction

The landscapes of the Great Lakes region incorporate dynamic interactions between the grasslands of the Great Plains, the eastern deciduous forests, and the boreal forests of North America. Patterns of climatic circulation give this region remarkably varied climate despite the fairly uniform topography. In the 500 km from southern Lake Michigan to Michigan's upper peninsula, growing season length drops from 180 to 90 days. Natural fire frequency drops from several fires per decade in the tall-grass prairies to several or no fires per 1,000 years in the maple-beech forests of Michigan. The Great Lakes themselves, the largest accumulation of freshwater lakes in the world, create "lake effect" climate zones, with more moderate temperature fluctuations complicating the environmental responses to climate change by interacting with the climate and acting as migration barriers. Urban development in the Great Lakes states is also variable, ranging from dense urban areas such as Chicago to remote wilderness such as Isle Royale and the Boundary Waters Canoe Area. Much of the area has been converted to commercial farmland or forests, but much also remains relatively undisturbed in wildlife reserves, undeveloped wetlands, national forests, and national parks. Documenting the extent and timing of the historical ecological change in such a diverse region presents a scientific challenge.

This chapter demonstrates the use of two different methods of reconstructing the historical vegetation of the Great Lakes region. Nineteenth century survey data are useful for reconstructing the forests that existed at the start of the period of European settlement, when natural ecosystems began to be greatly altered by an industrialized society. But because many impacts may have preceded these surveys and because natural ecosystems often have cyclic or directional natural changes caused by climate, fire, or plant succession, longer-term data are often required in order to place these nineteenth century "presettlement" ecosystems into a larger perspective. We use records of fossil pollen from the Great Lakes region to examine the relationship between this nineteenth century survey data and the vegetation record for the last 1,000 years.

General Land Office Survey Records of the Mid-nineteenth Century

The General Land Office Survey (GLO) of the mid-nineteenth century produced data that can now be used to classify the type of forests that existed at that time (Hutchison 1988). Surveyors delineated township boundaries using "bearing" and "witness" trees. The trees were chosen in a systematic manner, identified by species, recorded in log books, and blazed (marked) to enable relocation of the survey boundaries. Today, 150 years later, the blazed trees are almost all gone, but the data recorded during the survey remain. These data are a valuable record of mid-nineteenth century forests and can be used to develop maps of presettlement forest distribution.

Using a geographic information system (GIS; Clarke 1997), digitized maps from different time periods can be compared to analyze the changes that have occurred. A digitized vegetation map compiled from GLO maps (Stearns and Guntenspergen 1988; Fig. 6-1a) for the states of Michigan (Veatch 1959), Minnesota (Marschner 1974), and Wisconsin (Finley 1976) was compared with a digitized map of the forests of 1977-83 (Stearns and Guntenspergen 1988; Fig. 6-1b). The GLO surveys were conducted between about 1815 and 1866, and the modern forest map was compiled from the U.S. Forest Service's Fourth Forest Inventory.

Vegetation units on the maps were simplified in order to allow comparison between units used in the modern forest inventory and the three-state presettlement maps. Boreal forests consist mainly of white spruce (*Picea glauca*), balsam fir (*Abies balsamea*), and northern white cedar (*Thuja occidentalis*) and are mapped together with swamp conifer forest of black spruce (*P. mariana*) and tamarack (*Larix laricina*). Pine forests are dominated by white pine (*Pinus strobus*), red pine (*P. resinosa*), or jack pine (*P. banksiana*).

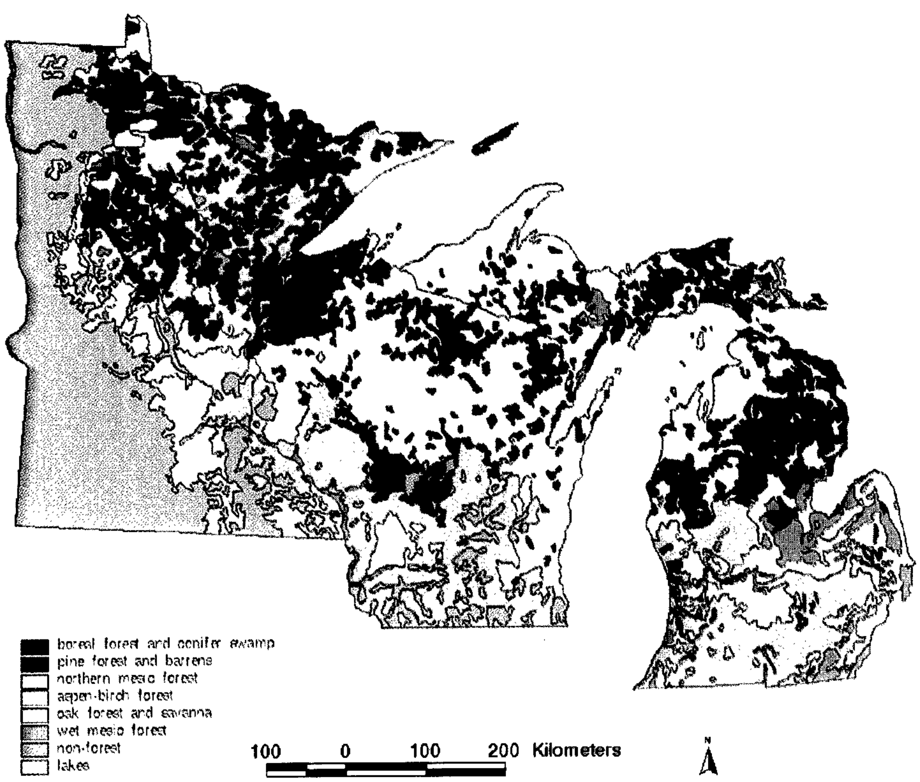

Fig. 6-1a. The presettlement forests of the Great Lakes states in the mid-1800's as reconstructed from records of the U.S. General Land Office Survey. Based on Stearns and Guntenspergen (1988).

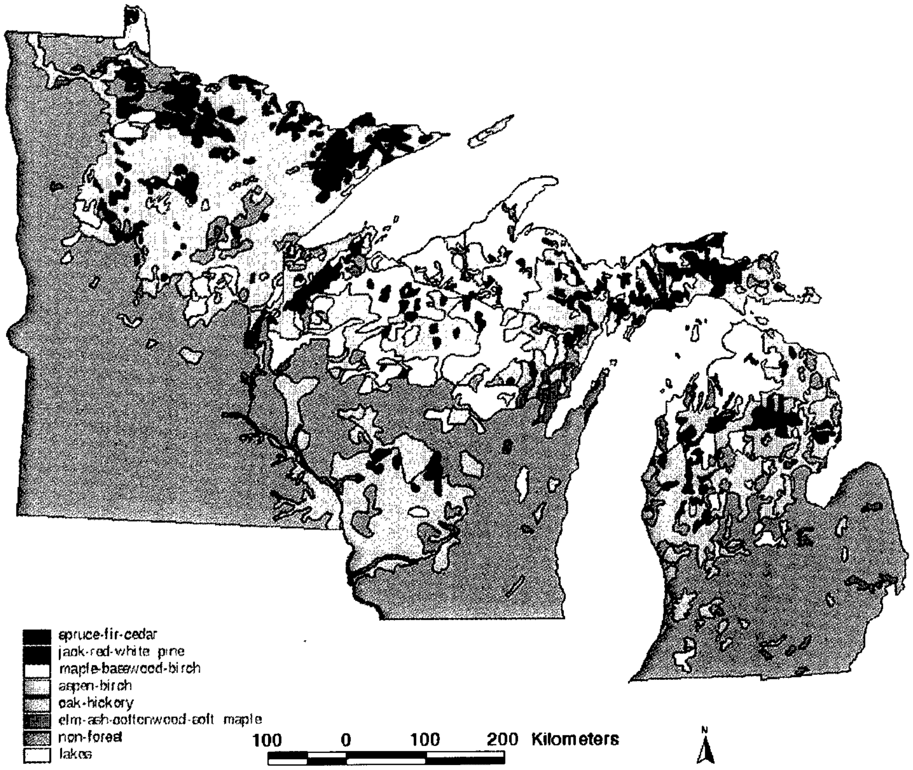

Fig. 6-1b. The modern forests of the Great Lakes states (1977 to 1983) as reconstructed from the U.S. Forest Service's Fourth Forest Inventory. Based on Stearns and Guntenspergen (1988).

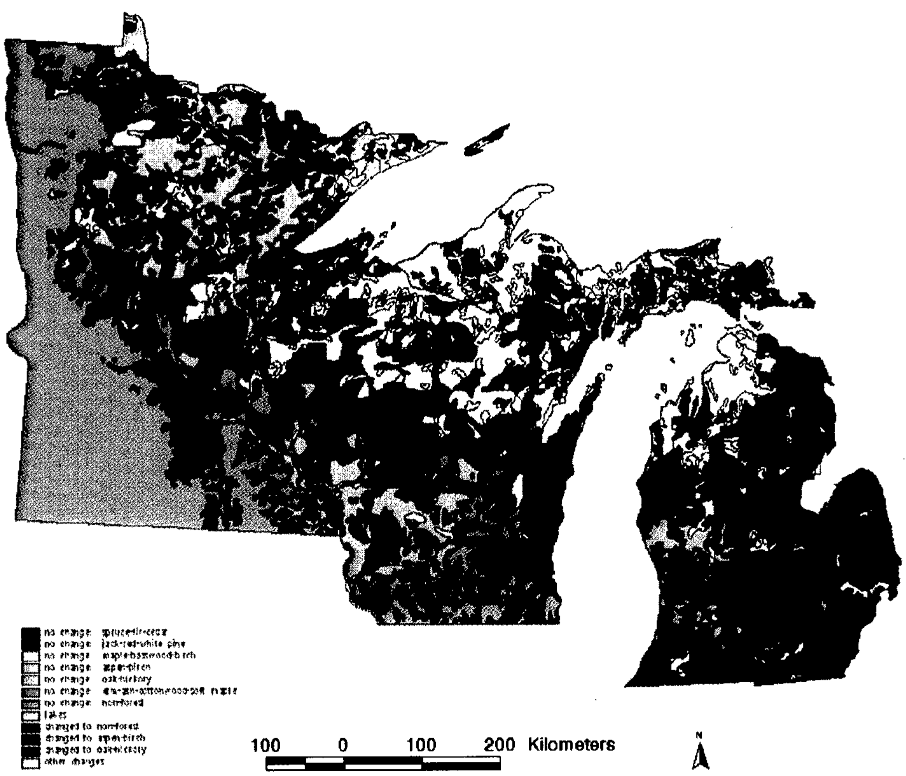

Fig. 6-1c. Map showing the changes in forest types between presettlement and modern maps.

Northern mesic forests are mostly mixtures of sugar maple (*Acer saccharum*), basswood (*Tilia americana*), yellow birch (*Betula alleghaniensis*), beech (*Fagus grandifolia*), and hemlock (*Tsuga canadensis*) with some oaks. Aspen-birch forests consist primarily of aspen (*Populus tremuloides*) and paper birch (*Betula papyrifera*). Oak forest consists of forest and savanna areas of red oak (*Quercus rubra*), black oak (*Q. velutina*), white oak (*Q. alba*), and bur oak (*Q. macrocarpa*). Wet mesic forests are lowland forests consisting primarily of American elm (*Ulmus americana*), green and black ash (*Fraxinus pennsylvanica* and *F. nigra*), and silver maple (*Acer saccharinum*). Nonforested areas include prairies, farmlands, and urban areas.

The maps produced for this study represent a broad overview and are generalized in regard to many specific locations and plant communities. Various agencies in all three states are currently producing much more detailed and accurate maps of presettlement and modern landcover classifications using GIS. Future research will allow more thorough mapping of even larger regions.

The presettlement and modern forest maps were overlaid by using a GIS to calculate the extent of area changing from one forest type to another (Fig. 6-1c). Two especially dramatic changes are evident between the maps: the conversion of forest to farmland and the conversion resulting from logging of other forest types to aspen-birch forest. The total amount of forested area declined by over 40%, mostly because of conversion of northern mesic forest and oak forest to farmland in the southern regions of the states. An additional 21% of the presettlement forests, mostly pine in the northern regions, was converted to early successional forests of aspen and birch following logging. Only 39% of the presettlement forests have not changed major type since settlement. Forest types that have declined the most precipitously are pine forest (-78%), boreal forest and conifer swamp (-62%), and northern mesic forest (-61%; Fig. 6-2). The only forest type that has increased is aspen-birch forest (+83%).

The average size of contiguous forests of the same type has also changed (Fig. 6-3). Forest patches (polygons on the map) of pine, oak, and northern mesic forest units are on average less than half of their presettlement sizes. In contrast, aspen-birch forest units and nonforested areas have more than doubled in patch size. These changes in patch size influence the distribution and migration of plant and animal species and may influence other processes, such as fire. However, some of the patch size differences may be caused by the different survey methods used in producing each map. The more detailed and accurate maps currently being produced of the Great Lakes states should be useful in clarifying this issue.

These maps demonstrate that although much of the region is less impacted than other areas to the south and east, extreme environmental changes have occurred in Great Lakes forests over the last 150 years. The severity of these changes can be better appreciated when they are examined in the longer term perspective of the last 1,000 years.

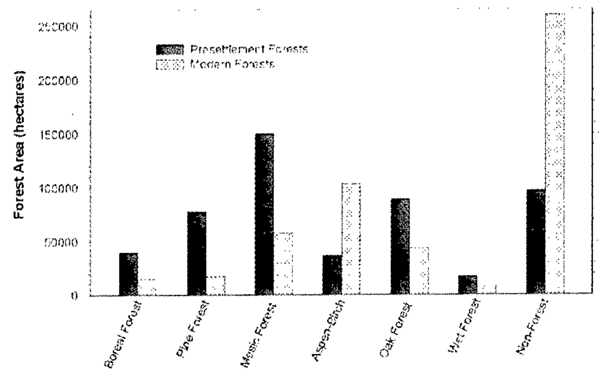

Fig. 6-2: Changes in area covered by major forest types in the Great Lakes states between presettlement and modern times as calculated from Fig. 6-1c.

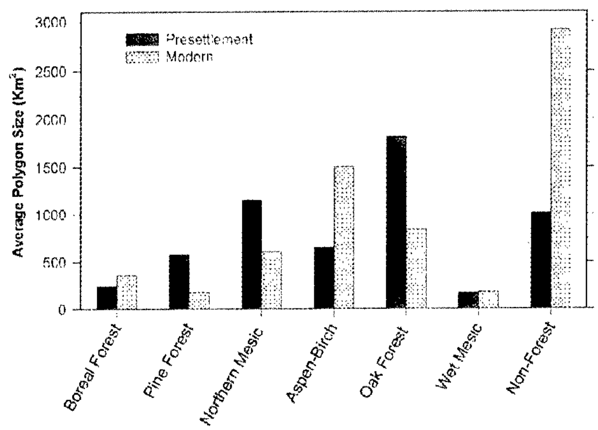

Fig. 6-3: The average size of contiguous presettlement and modern forest patches in the Great Lakes states as calculated from Fig. 6-1c.

Landcover Changes in the Last 1,000 Years

The Great Lakes states offer uniquely detailed data on historic and paleoecological environments over the last 10,000 years. This pilot project, though, will describe only data covering the most recent 1,000 years. The sediments at the bottom of many lakes are repositories of information on environmental history, containing abundant fossil pollen, diatoms, ostracodes, cladocerans, charcoal, and sediment chemistry. The North American Pollen Database (a public domain database developed by the National Geophysical Data Center) contains data from over 150 sites in

the Great Lakes states. An equivalent number of records, many not yet in the public database, have recently been entered into a regional database for Wisconsin and Michigan (M. B. Davis, University of Minnesota, unpublished data). This database greatly extends the detail in the northern portion of these states beyond what was previously available (Webb et al. 1983).

The study of fossil pollen (palynology) from lake and bog sediments is an excellent method for reconstructing past environments (Faegri and Iversen 1989). The fossil pollen is studied by first treating the sediment with a series of chemicals that digest most of the materials in the sediment except the pollen (pollen walls are made of a very resistant material). Then the pollen from the sediment can be identified by using microscopes.

Many pollen samples are taken from a single lake, usually by extracting a core of the lake sediment. Each pollen sample is aged by dating portions of the core with radiocarbon or lead isotopes. Although some studies have produced records as detailed as one sample per decade, this kind of resolution over a 10,000-year period would be prohibitively expensive, requiring the analysis of 1,000 samples. Most sediment cores are sampled less extensively, producing one sample to represent every 50 to 200 years.

Each pollen sample can yield up to 50 different pollen types, each type representing a different plant group. Pollen analysis is especially useful in the eastern deciduous forests of North America because many important tree species produce their own distinctive pollen type. The data can be used to detect past changes at a single site, or multiple sites can be combined to reconstruct past migrations of ecosystems or plant species over the landscape (Davis et al. 1986).

Because of the detailed information in each sample, summarizing the data over a region is difficult, as only the predominant pollen types can be presented. Often, complex statistical analyses are used to reduce the myriad pollen types into indexes representing similar species groups. Some pollen types, such as the goosefoot family (Chenopodiaceae) and the sagebrush group (*Artemisia* spp.), grow well in recently disturbed areas, such as at the edges of farm fields. These pollen types are excellent indicators of disturbances in ecosystems. Other taxa, such as beech (*Fagus grandifolia*), grow in old-growth forests that have not been disturbed for centuries.

The abundant fossil pollen records from northern Wisconsin and Michigan provide a record of past forest changes which is extremely detailed. Selected sites were used to compare the modern land cover (1970-90; Fig. 6-4a) with land covers of the presettlement era (1830-60; Fig. 6-4b) and of about 1,000 years ago (Fig. 6-4c). Pollen from sediment cores at each site (represented by pie charts in

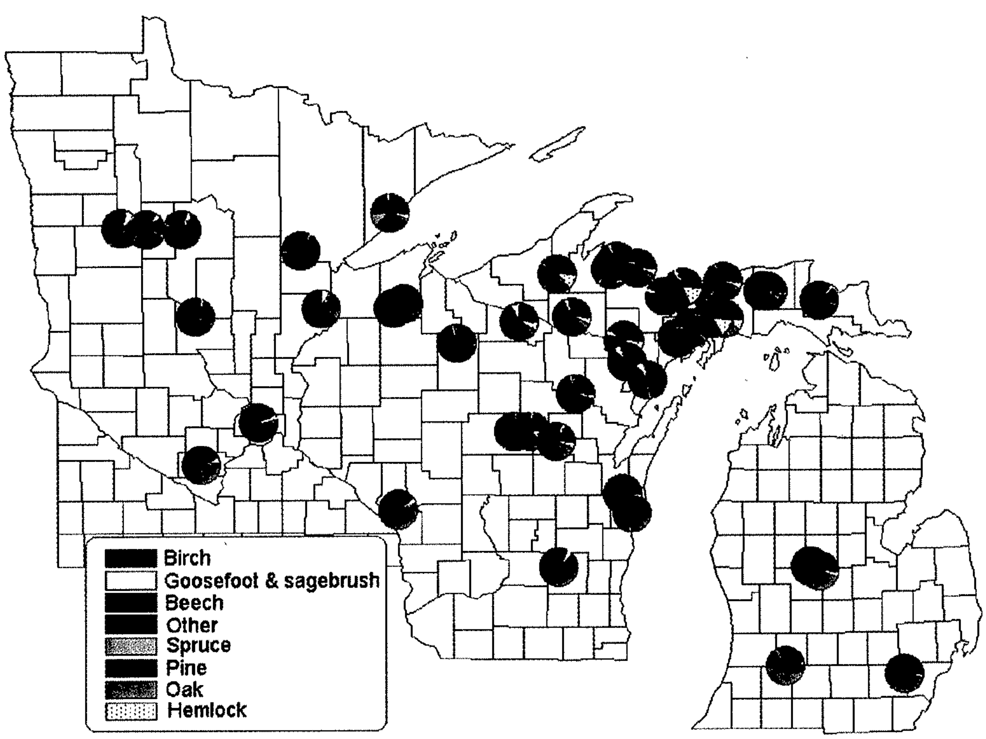

Fig. 6-4a: Great Lakes states pollen sites showing modern major pollen types measured at the tops of sediment cores in lakes and bogs.

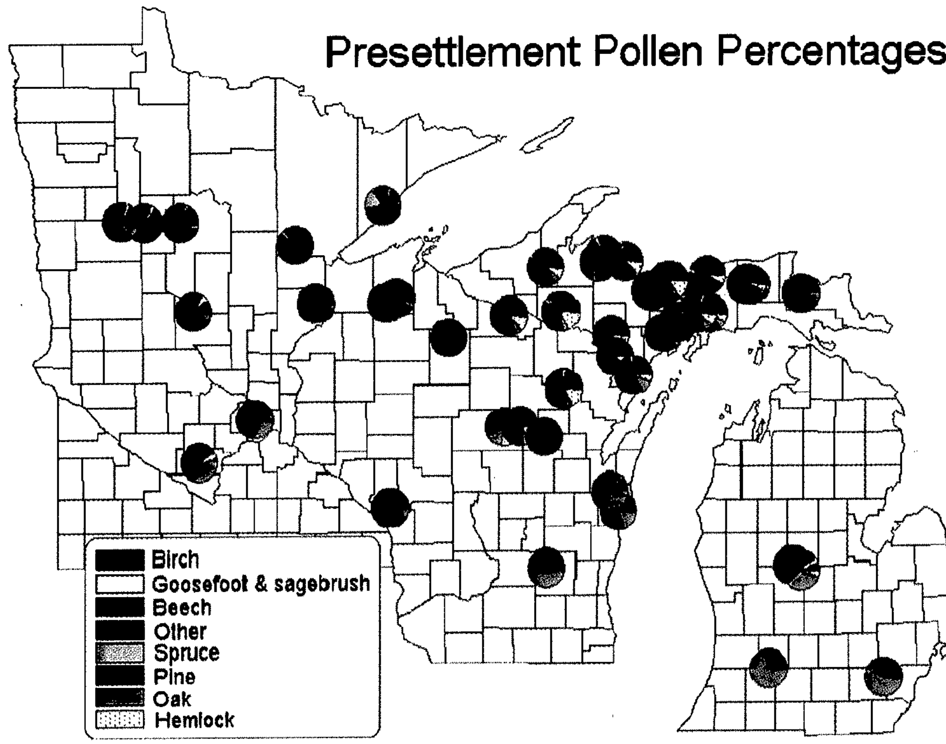

Fig. 6-4b: Great Lakes states pollen sites showing major pollen types just prior to the settlement horizon (about 150 years ago).

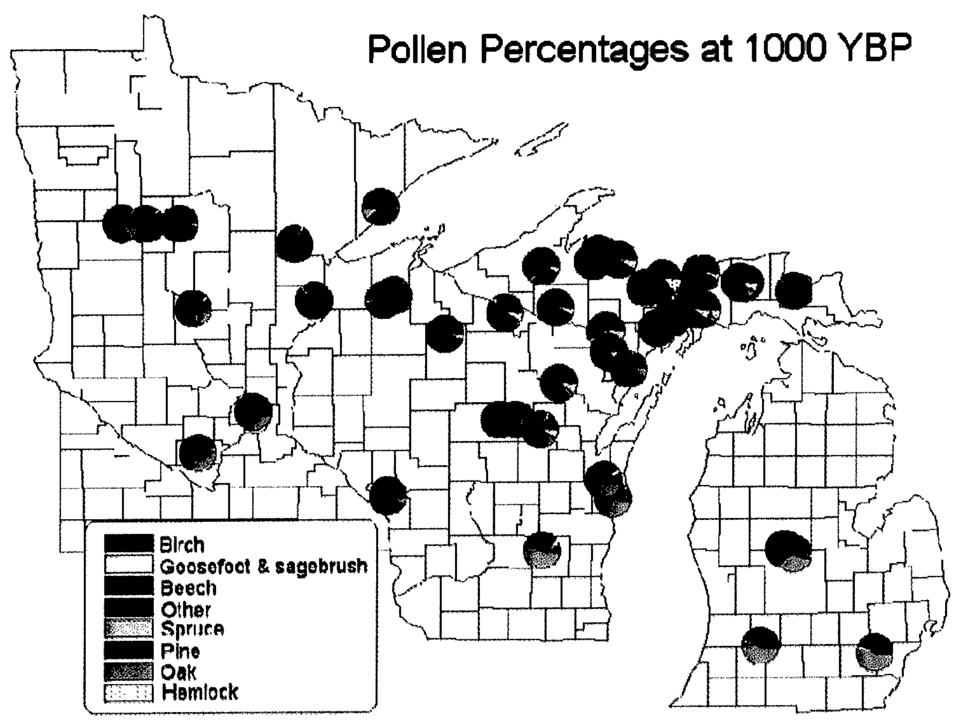

Fig. 6-4c: Great Lakes states pollen sites showing major pollen types about 1,000 years ago.

the figures) furnishes recent and Holocene fossil records, many of which extend back to the retreat of the Pleistocene glaciers about 14,000 years ago (12,000 B.C.) in the south to 11,000 years ago (9,000 B.C.) in the north. Differences between the presettlement and modern surface samples reflect the forest changes occurring between the mid-nineteenth century GLO survey and recent U.S. Forest Service survey (Fig. 6-1c). Although almost all of these samples were taken in undisturbed forested areas, the percentage of disturbance indicators (goosefoot family and sagebrush) increased, especially in the South where much nearby forest was converted to nonforest. In the North, birch usually increased at the expense of white pine as a result of logging. Beech decreased in all but the least disturbed areas.

Comparison of Changes: 1,000 Years Ago to Presettlement Versus Presettlement to Current

For this chapter, we have contrasted the amount of vegetation change from 1,000 years ago to the presettlement time horizon (a period of about 850 years) with the amount of change taking place between the presettlement horizon and the current era (about 150 years). The data from each pollen record were analyzed by using a statistical method that plots each sample in a multidimensional space using the percentage values for each pollen type in the sample. The distances between the three samples at each site in this multidimensional space (Squared Cord Distance) were then calculated.

The results demonstrate that the average amount of change in pollen types was 2.4 times greater during the 150 years since settlement than during the previous 850 years (Fig. 6-5). This difference is statistically significant ($P = 0.0015$ for a one-tailed t-test following a log-normal conversion). Recent changes also have a larger range of variability; some sites have changed radically, while others have changed little since settlement. The magnitude of these recent changes can be fully appreciated by considering that no records were taken from cultivated fields or urban areas. Most of the sampling sites were in relatively unimpacted forests which would most likely have been recorded in Fig. 6-1c as "unchanged."

The fossil pollen results support the comparisons of presettlement GLO and modern forest survey data from the first part of this project. The mid-nineteenth century GLO data could not be used to represent general presettlement conditions if forests were changing rapidly throughout the last several hundred years. The results of this pollen analysis suggest that rates of forest change prior to settlement were minor when compared to rates of change after settlement (Cole 1995). As a result, GLO survey data do represent a generalized presettlement condition. More detailed analysis of the fossil pollen demonstrates environmental changes due to fluctuating climate and other factors prior

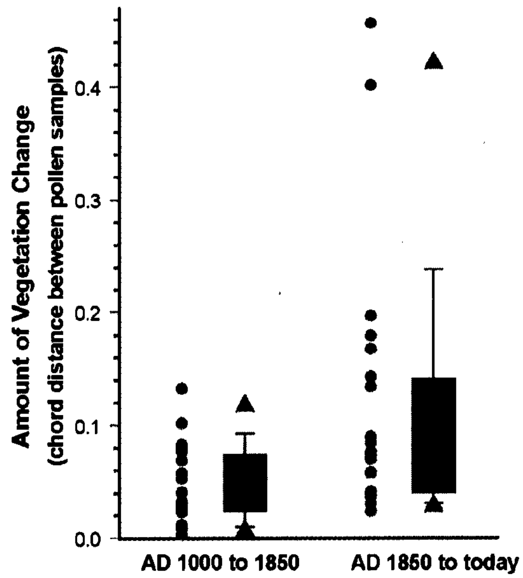

Fig. 6-5: Scatterplots of squared cord distance values between modern and presettlement pollen samples and between 1,000-year-old samples and presettlement samples. Box and whisker charts to the right of each scatterplot show the 10th, 25th, 50th, 75th, and 90th percentiles. Open triangles show the 5th and 95th percentiles.

to settlement, but these changes are generally of a much lower magnitude than those occurring since European settlement.

These fossil pollen data are important in providing a regional vegetation history at a resolution unobtainable through any other method. The use of GIS permits the overlaying of digitized data on topography, climate, forest cover, and pollen data, allowing for analysis of past forest changes and its relation to soils, topography, or proximity to the lakes.

The power of this fossil pollen data is that the last several thousand years of environmental history can be examined, providing a more meaningful record of change than the relatively simplistic comparison of presettlement versus postsettlement. Directions and past rates of change can be reconstructed in a dynamic manner investigating past natural changes resulting from shifts in climate, plant migration, and plant succession. These changes can be compared with the recent anthropogenic changes to evaluate the nature and magnitude of change resulting from these very different forces.

Acknowledgments

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Chapter 7: Presettlement and Contemporary Vegetation Patterns Along Two Navigation Reaches of the Upper Mississippi River

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Abstract. Restoration efforts within large floodplain–river ecosystems should rely heavily upon knowledge of these systems prior to large-scale alterations by humans. Unfortunately, most large rivers in the north temperate zone were modified centuries ago—long before any ecological investigations. In many parts of the United States, though, historical records do exist which contain quantifiable data about the "natural" conditions of a region. In this study, we reconstructed presettlement vegetation patterns along two navigation reaches of the upper Mississippi River using data recorded in 1816 by surveyors from the U.S. General Land Office (GLO). Contrary to many previous studies indicating forest as the dominant community type along the floodplains of the upper Mississippi River, our results indicate that prairie was a dominant community type. Savannas, open woodlands, and closed forests were also important features. While flood regime has long been regarded as the master variable influencing productivity and biodiversity within large floodplain–river ecosystems, we propose that fire also played an important role in maintaining some plant communities on the floodplains of the upper Mississippi River.

Introduction

In 1797, French cartographer Nicolas de Finiels mapped the vast floodplain formed by the confluence of three of North America's greatest rivers: the Mississippi, Missouri, and Illinois. On his map he labeled the floodplain "Grande Prairie," and in his notes he described his view from high atop the Illinois bluffs:

> You can from [here] admire the confluences of the Mississippi, Missouri, and Illinois rivers, get drunk on an indescribable spectacle, and lose yourself in the profound meditations that it inspires. If you swing your eyes back toward the west and the north, your gaze is consumed by the vast plain that proceeds up the Mississippi from St. Charles; prairies, clumps of woods, ponds, and streams dissect it, and the irregular loops of the river seem to want to imprison it. (de Finiels 1797, p. 83)

Later, in 1811, a frontiersman named Henry M. Brackenridge described his view of the same confluence region from the bluffs near St. Charles on the Missouri side of the valley:

> . . . we behold the ocean of prairie, with islets at intervals. The whole extent perfectly level, covered with long, waving grass, and at every moment changing color from the shadows cast by the passing clouds. In some places there stands a solitary tree, of cottonwood or walnut, of enormous size, but, from the distance, diminished to a shrub. A hundred thousand acres of the finest land are under the eye at once, yet in all this space there is but one little cultivated spot to be seen. (Brackenridge 1814, as cited in Schroeder 1981, p. 17)

While historical descriptions such as these are valuable sources of information about former landscapes, they rarely provide sufficient detail to be useful to natural resource managers or restoration planners. Until recently, one of the most useful sources of historical data regarding the unmodified upper Mississippi River ecosystem has largely been overlooked. Survey records of the U.S. General Land Office (GLO) have been used to reconstruct presettlement landscapes and vegetation patterns for many upland regions of the United States, but not for the floodplains along the upper Mississippi River. General Land Office records are particularly useful to ecologists because they contain detailed measurements of presettlement tree composition and timberland structure, as well as maps showing the location and extent of former prairies, swamps, ponds, rivers, streams, marshlands, and timberlands. Unlike historical descriptions, the GLO records provide us with quantifiable data that can be used to reconstruct a baseline condition.

Knowing as much as possible about presettlement baseline characteristics of the upper Mississippi River valley is important. At the species level, natural resource managers can use presettlement baselines to formulate management plans on public lands; for example, determining what kinds of trees should be planted on islands. At the community level, a presettlement baseline can identify threatened or endangered ecosystems; for example, by showing whether forests dominated the floodplain or if other plant communities were prevalent. At the landscape level, a presettlement baseline can provide valuable insight into the natural processes that maintain biodiversity; for example, if fire were an important disturbance factor in shaping presettlement vegetation patterns.

In this study, we used GLO data to reconstruct presettlement baseline vegetation patterns along navigation reaches 25 and 26 of the upper Mississippi River (Fig. 7-1). Reaches are sections of river between two navigation dams; those along the upper Mississippi River range between 8 and 80 km in length and are numbered consecutively, starting upstream with Reach 1 near Minneapolis, Minnesota, and culminating downstream with Reach 26 near St. Louis, Missouri (total distance 1,072 km). Results of this study provide quantifiable data about the former plant communities native to this part of North America's largest floodplain–river ecosystem. In conjunction with modern data, we discuss some of the plant community changes resulting from European-American settlement of the region over the past 180 years.

Methods

In 1785, the GLO began developing the American Rectangular Survey System to dispense land to settlers in western territories. The new survey system, which still dictates most public land divisions today, divided the landscape into a grid of townships, each 93.2 km^2 (36 mi^2). Each township was further subdivided into 36 sections, each 2.6 km^2 (1 mi^2; Fig. 7-2). At each section corner and midway between section corners, GLO surveyors set a post in the ground. In timbered lands, two nearby trees were selected and marked as bearing trees to identify and perpetuate corners. After establishing each corner post, the surveyor recorded the common name and diameter at breast height (dbh) of the bearing trees, along with their distances and compass bearings from the post. If trees were not present, an earthen mound was erected into which the post was set, and "prairie" was written in field notes. Occasionally, only one bearing tree was recorded at a corner, presumably because a second tree was not in close proximity.

In addition to bearing trees, line trees encountered directly on section lines and between corners were similarly recorded. After each surveyed mile, the surveyor noted the type of terrain, soil, undergrowth vegetation, and timber, plus any unusual features. We compiled all these data from microfiche copies of the original GLO field notes obtained

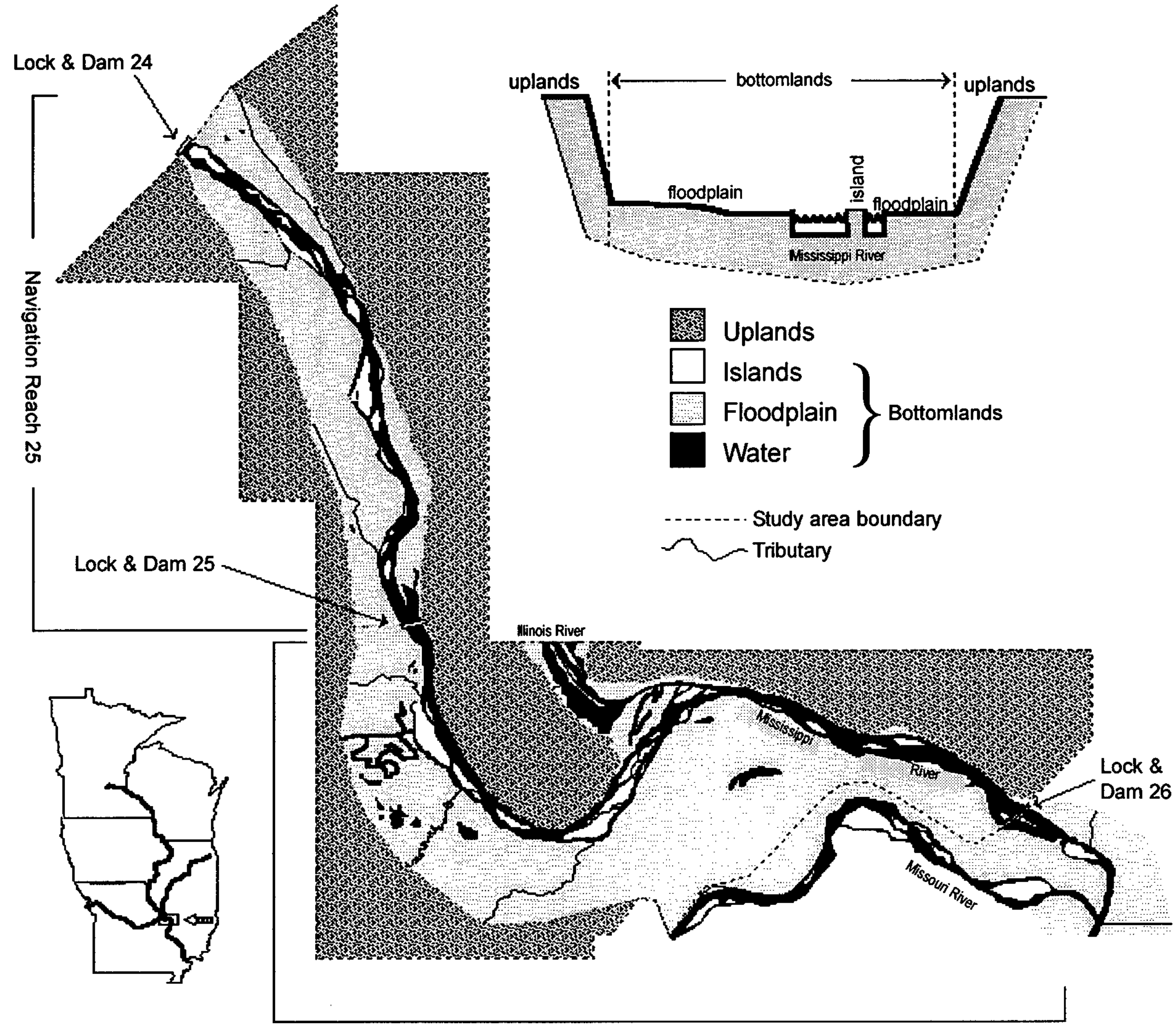

Fig. 7-1. Map of study area showing location of navigation reaches 25 and 26, upper Mississippi River. Cross section diagram shows the three river valley categories (island, floodplain, upland) used to analyze and compare data. Total area = 191,622 ha (473,492 ac).

from the Missouri Department of Natural Resources and the Illinois State Archives.

The GLO completed its initial surveys of the Reaches 25 and 26 study area in 1816. American settlement of the region was preceded by French and Spanish (nearby St. Louis was founded in 1764). The presence of European inhabitants in the decades before the GLO survey negate any real possibility of reconstructing the absolute "pre-European settlement conditions." Since the earlier inhabitants relied mainly on subsistence agriculture and because their numbers were relatively low, however, the GLO records are still one of our best sources of historical data regarding presettlement conditions.

Data from surveyors' field notes were compiled according to location among three river valley categories: islands, floodplains, and uplands (see Fig. 7-1 inset). Importance values were then calculated to summarize presettlement tree composition for each river valley category. The numerical importance value for a given tree species can range between 0 and 200 based on two factors, average tree diameter and tree frequency. A tree species can have a higher importance value than other species because it was more frequently recorded by the GLO surveyors or because the diameters recorded were larger than other species. Of course, a species could also have a high importance value due to a combination of both factors. Tree diameter is a

Fig. 7-2. Section lines of the U.S. General Land Office surveys are permanently etched across the landscape because many country roads were built along these lines orientated north-south and east-west. The large square in the center of the picture is a 2.6 km² (1 mi²) section. Photograph by Mary Craig, USGS Biological Resources Division, Environmental Management Technical Center.

good indicator of overall tree size and was used to compute basal area per tree. Dividing the total basal area per species by the total basal area of all species provides an estimate of relative dominance. Relative density is the number of individual trees recorded per species divided by the total number of trees recorded. An importance value for each species was then obtained by adding relative dominance and relative density. Since importance values are based on two sets of relative values, their sum total will always equal 200 (Table 7-1).

Tree density for each river valley category was estimated by computing the square root of the mean area per tree ($\sqrt{M}$), which is a function of mean tree distance (Cottam and Curtis 1956). The mathematical computation of tree density using GLO data depends upon the number of bearing trees recorded at each corner. As previously mentioned, most frequently the GLO surveyors recorded two bearing trees, but sometimes only one bearing tree was used, presumably because no other tree was nearby. In some cases though, three and four bearing trees were recorded. Many researchers choose to use only the closest bearing tree distance at each corner to compute the $\sqrt{M}$, and they discard other bearing tree distances. While this method is one way of standardizing the data, valuable information is lost. We incorporated weighted averaging so that all bearing tree distances could be used in the density computation. First, we determined the mean bearing tree distance among corners having either one, two, three, or four bearing trees. Then, we computed the tree density for each of these four groups. The density multiplied by the frequency of corners within each group provided a weighted measure. These weights were summed and then divided by the total sample size to estimate overall tree density. Tree densities were then used to characterize the dominant community type: prairie, savanna, woodland, or forest (Fig. 7-3).

A geographic information system (GIS) was used to evaluate landcover changes occurring within the study area since the time of the original surveys (1816). For each township, the GLO produced a plat map delineating the location, size, and shape of any prairies, timberlands, marshlands, ponds, rivers, etc., as well as the arrangement of township and section lines. Since township and section lines are also delineated on modern U.S. Geological Survey (USGS) quadrangle maps, it is possible to make reliable georeferenced GIS landcover maps using GLO plats. Spatial changes in land cover over time were determined by comparing our presettlement map to a GIS landcover map compiled from aerial photographs (bottomlands) and satellite imagery (uplands).

Table 7-1. Presettlement tree composition among three river valley categories within reaches 25 and 26 of the upper Mississippi River. Number of trees, relative dominance (rel. dom[1]), relative density (rel. den), and importance value (IV; rel. dom. + rel. den.) from GLO bearing and line tree measurements. Species are ranked by importance value for the entire study area. Importance values 10 or greater are printed in bold.

	Islands				Floodplains				Uplands				Entire Study Area			
Common/scientific name	# Trees	Rel. Dom.	Rel. Den.	I.V.	# Trees	Rel. Dom.	Rel. Den.	I.V.	# Trees	Rel. Dom.	Rel. Den.	I.V.	# Trees	Rel. Dom.	Rel. Den.	I.V.
White oak (*Quercus alba*)[1]	3	4	2	6	53	9	7	**16**	830	41	35	**76**	886	33	27	**60**
Black oak (*Q. velutina*)	*	*	*	*	*	*	*	*	674	33	28	**61**	674	25	20	**45**
Hickory (*Carya* spp.)	*	*	*	*	50	4	6	**10**	338	9	14	**23**	388	8	12	**20**
Elm (*Ulmus* spp.)	18	10	11	**21**	105	13	13	**26**	97	3	4	7	220	5	7	**12**
Pin oak (*Q. palustris*)[2]	*	*	*	*	164	24	21	**45**	1	0	0	0	166	5	5	**10**
Cottonwood (*Populus deltoides*)	32	36	19	**55**	62	12	8	**20**	6	1	0	1	100	4	3	7
Hackberry (*Celtis occidentalis*)	38	12	23	**35**	77	7	10	**17**	19	0	1	1	134	2	4	6
Ash (*Fraxinus* spp.)	10	9	6	**15**	54	6	7	**13**	46	1	2	3	110	3	3	6
Post oak (*Q. stellata*)	*	*	*	*	10	0	1	1	87	3	4	7	97	2	3	5
Blackjack oak (*Q. marilandica*)	*	*	*	*	4	0	1	1	95	2	4	6	99	2	3	5
Silver maple (*Acer saccharinum*)	11	6	7	**13**	52	10	7	**17**	1	0	0	0	64	2	2	4
Willow (*Salix* spp.)	7	1	4	5	39	3	5	8	*	*	*	*	46	1	1	2
Basswood (*Tilia americana*)	*	*	*	*	2	1	0	1	26	1	1	2	28	1	1	2
Sugar maple (*Acer saccharum*)	*	*	*	*	*	*	*	*	32	1	1	2	32	1	1	2
Boxelder (*Acer negundo*)	28	10	17	**27**	13	1	1	2	4	1	0	1	45	1	1	2
Other taxa combined[3]	19	12	11	23	100	10	13	23	139	4	6	10	257	5	7	12
Totals	166	100	100	200	785	100	100	200	2,395	100	100	200	3,346	100	100	200

[1] on islands and floodplains, white oak was probably swamp white oak, overcup oak, and/or bur oak.
[2] misidentified by GLO surveyors on the floodplain as black oak.
[3] other taxa were sycamore, walnut, red oak, dogwood, mulberry, pecan, red bud, sassafras, black locust, river birch, bur oak, persimmon, honey locust, coffee tree, hawthorn, buckeye, crab tree, cherry tree, scrub oak, overcup oak, hornbeam, ironwood, pawpaw, and spanish oak.

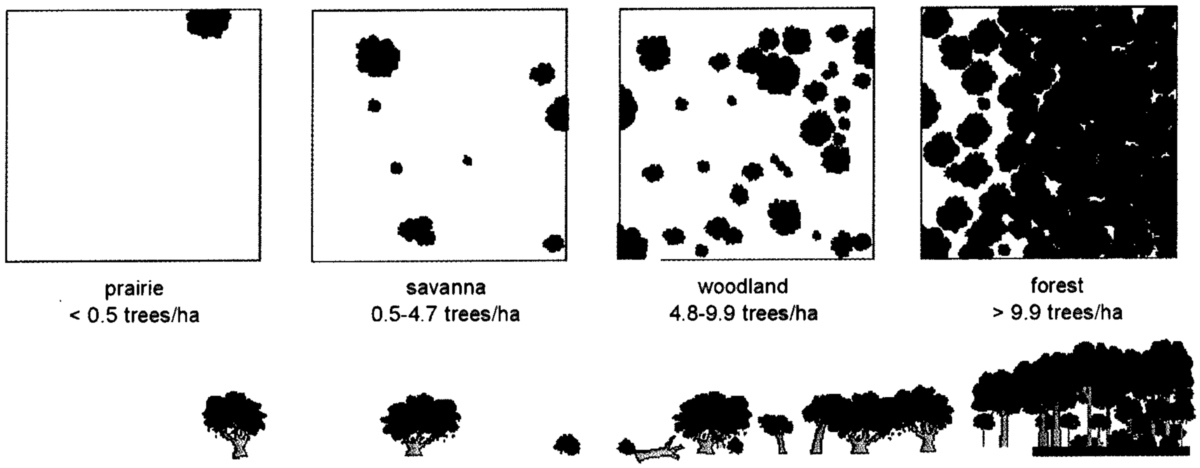

Fig. 7-3. Prairie-forest continuum and tree density criteria used to generalize presettlement communities (adapted from Anderson and Anderson 1975, and Packard and Mutel 1997).

Results and Discussion

The Presettlement Landscape

The presettlement map reveals that prairie was once the dominant community type on the floodplain (Fig. 7-4). Most prairies were vast, covering thousands of acres on the high and intermediate elevations. Often, these large tracts of prairie were separated only by narrow belts of timber growing along tributaries that meandered across the floodplain. Timber was generally restricted to the islands, the banks of the Mississippi River and its tributaries, and the surrounding uplands. These patterns challenge some presettlement vegetation maps of the Midwest that show forest vegetation as the dominant community type along the Mississippi and other large floodplain–river systems (Transeau 1935; Küchler 1964; Anderson 1970). These other presettlement maps, however, use too coarse a scale to reveal the importance of prairie on the floodplains of the upper Mississippi River.

Presettlement tree density estimates indicate dense forests generally prevailed on islands (115 trees/ha), while more open woodland communities prevailed on the floodplain (64 trees/ha). Tree density was lowest on the uplands adjacent to the river (37 trees/ha), indicating savanna was the dominant community type.

Tree species importance values differed among river valley categories in 1816 (Table 7-1). On islands, where flood disturbance was likely the most frequent, species that produce light seeds dominated. Cottonwood, a pioneer species requiring newly exposed mud flats and full sunlight in order to become established, had the highest importance value at 55. Associated species were hackberry, boxelder, American elm, green ash, and silver maple. Species producing light seeds were also important components on the floodplain, but they were less important than the heavy nut-producing pin oak, which had the highest importance value at 45. Shagbark and shellbark hickory were also important nut-producing trees on the floodplain with a combined importance value of 15. In the presettlement period, oak and hickory communities probably occurred on the better drained soils of higher elevation terraces, which were less prone to flooding. These terraces cover vast regions of the study area on the floodplain away from the main channel of the Mississippi River. The creation of floodplain terraces along the upper Mississippi River can be traced back to the retreat of continental icesheets. During deglaciation, many floodplain terraces were formed by outwash of meltwaters and catastrophic flooding from the outburst of glacial lakes. In the uplands along the river valley, presettlement species composition paralleled the dominants recognized for the Central Hardwood Forest Region, as classified by the Society of American Foresters (Eyre 1980). White oak and black oak were the dominant species with importance values of 76 and 61, respectively. Hickories were important associates with a combined importance value of 23.

Ecologists studying presettlement vegetation patterns in the uplands of the Midwest have long attributed the maintenance of prairies, savannas, and woodlands to disturbance by fire. Without fire, grassland communities in the Midwest are invaded by trees and convert to forest. The rate of conversion in the absence of fire can be very rapid, especially for savanna and woodland communities, which characteristically have grassy ground cover and widely spaced trees (Fig. 7-3). When fire disturbance is removed from these communities, new trees can quickly become established, grow up into the overstory, and shade out the grasses and forbs. The disturbance regime that helped maintain a diverse mosaic of communities across upland landscapes

is attributed to lightning strikes and annual fires set by Native Americans in the centuries before the arrival of Europeans.

According to the GLO data, the Mississippi River floodplain was once covered by prairies with trees growing along the river banks and tributaries. These landscape patterns are similar to those found on many upland sites where prairies covered level to gently rolling terrain and trees grew in areas protected from fire, such as along streams, in ravines, and on hillsides. The dominance of floodplain prairies and the high importance of oak and hickory during the presettlement period may indicate that fires frequently swept across both upland and floodplain landscapes. Many Native American cultures flourished within the upper Mississippi River valley, and they likely extended the burning practices used on surrounding upland landscapes to the floodplain as well. In contrast to fire, flooding presumably played a more important role on islands and on other low elevations near the river channel and its tributaries.

The Contemporary Landscape

The landscape of the study area has changed considerably over the past 180 years. Prairie was once the dominant community, covering 46.3% of the bottomlands. Today, the prairies have largely been replaced by agricultural fields (Fig. 7-5). While prairies can still be found on some parts of the floodplain (5.6%), the current limited extent of this community and its associated savannas and woodlands should be a primary concern for conservationists. The timberlands that once covered 35.0% of the bottomlands are now reduced to 18.6%. Many of these remaining timberlands lack the diversity of their presettlement counterparts due to past logging, river impoundment, and fire suppression (Nelson et al. 1994; Nelson and Sparks 1998). Tree species diversity is also lacking on many bottomlands because forests are restricted to the most flood-prone areas (islands and river margins) and thus are dominated by flood-tolerant taxa, such as silver maple and ash. Gone are most of the higher elevation oak–hickory woodlands and savannas. Timberlands on the uplands have been reduced from 98.5% to 40.8%. The remaining upland timber occurs on steep terrain along the eastern side of the Mississippi River in Illinois. Since the upland landcover data were obtained from satellite imagery taken in the late 1970's and early 1980's, it is likely that the amount of upland timber occurring now is less than our reported value (40.8%).

A Conceptual Model

The GLO data were also used to help develop a conceptual model of the presettlement river valley ecosystem (Fig. 7-6). Tree composition and tree densities indicate oak savannas and woodlands were once widespread, while plat maps confirm the dominance of prairies on the floodplain. The maintenance of prairies, savannas, and woodlands has long been attributed to frequent disturbance by fire for many upland regions of the Midwest. However, it seems likely that fire also was important for some large floodplain–river ecosystems like the upper Mississippi. Floodplain prairies must have been maintained by some disturbance regime(s), otherwise they would have been overtaken by trees long ago. Conventional wisdom dictates that flood regime was the key factor. However, flood disturbance alone can not explain the maintenance of most floodplain prairies. Degree of flooding is a function of elevation at any given point on the floodplain, and since most of the presettlement prairies occurred on intermediate to high floodplain elevations, they likely often became very dry in late summer and early autumn. Thus, fire was likely the dominant disturbance responsible for maintaining floodplain prairies on these higher elevations. On the generally low elevation sites on islands and along the margins of the Mississippi River, dense forests of cottonwood-elm-maple prevailed. The development and maintenance of this community type occurred on sites subject to frequent flooding, which was probably the dominant disturbance factor on islands and other low-lying areas nearest the river, along side-channels, and along tributaries. Some communities located at intermediate elevations were probably influenced by floods in wet years and fires during dry years. These highly dynamic intermediate zones on the floodplain may have supported savannas and woodlands. In the uplands, as in the high terraces of the floodplain, fire was the principal disturbance factor influencing the maintenance of woodland and savanna communities. Hill prairies that were once extensive along the bluffs of the Mississippi River may have been maintained by fires that originated in the bottomlands and swept up the valley slopes.

Conclusions

The results of this study can be used to help implement ecosystem management plans on Federal lands of the U.S. Army Corps of Engineers and the U.S. Fish and Wildlife Service, as well as in many State-managed conservation areas located along the upper Mississippi River. One goal of ecosystem management should be to recover some of the biological integrity lost by alteration of the landscape during the past 180 years. On the bottomlands, the formerly extensive prairie, savanna, and woodland communities are either nonexistent or have been reduced to small, fragmented patches. Restoration of these communities can be accomplished using prescribed disturbance regimes (fire and flooding) on lands within some Federal wildlife refuges and in some State-managed wildlife areas. Any efforts in the uplands to prevent further forest fragmentation or losses should be encouraged. The remaining hill prairies should be periodically burned to prevent their conversion to closed-canopy forest.

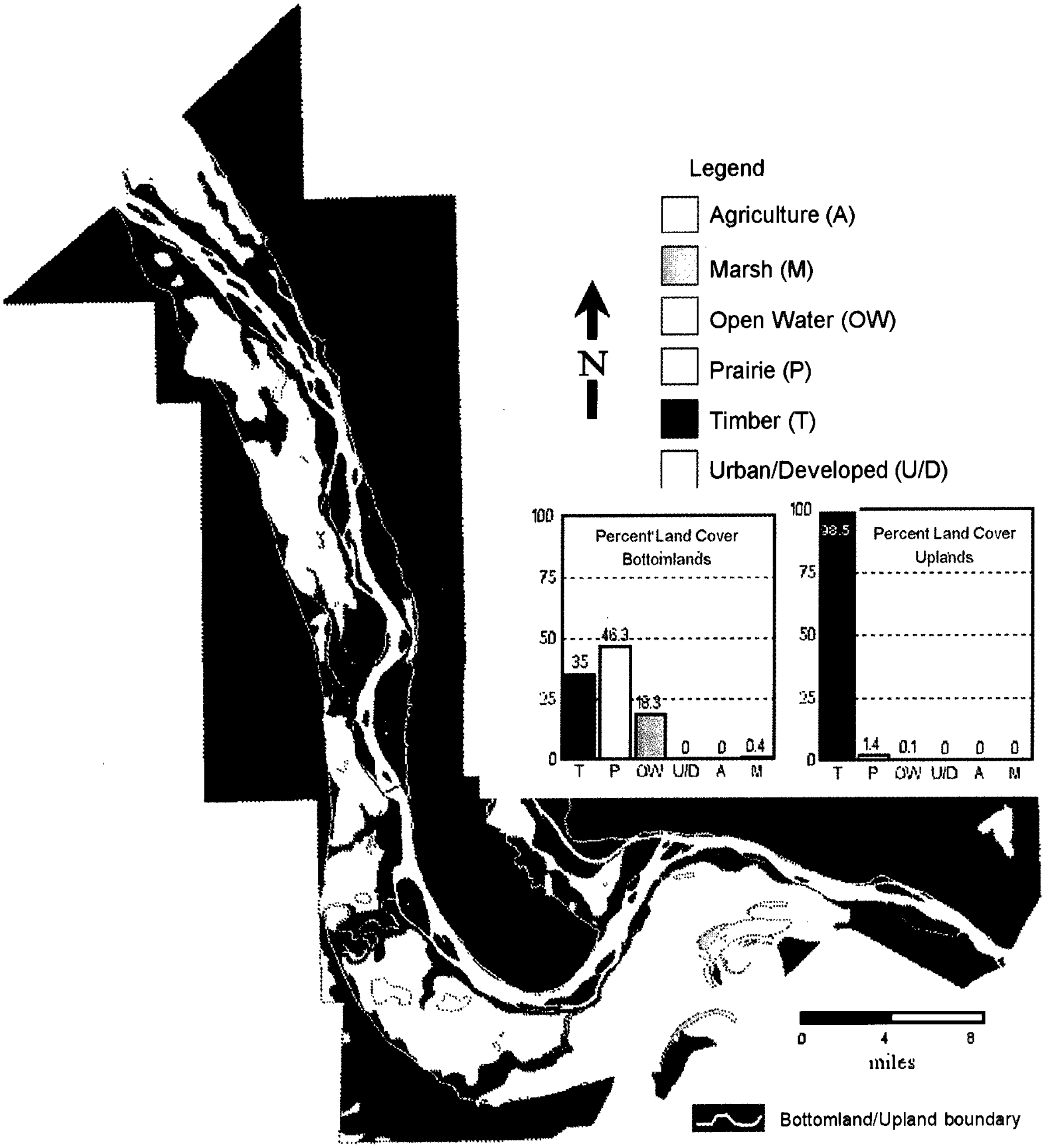

Fig. 7-4. Geographic information system map showing presettlement (1816) land cover along navigation reaches 25 and 26 of the upper Mississippi River. Landcover data were obtained from General Land Office township plat maps and transferred to 1:24,000 USGS topographic quadrangles. Graphs show percent land cover for timber, prairie, open water, urban/developed, agriculture, and marsh for the upland and bottomland regions within the study area.

Acknowledgments

Funding for this project was provided by the Long Term Resource Monitoring Program for the Upper Mississippi River System. The program is supported by the U.S. Army Corps of Engineers and the U.S. Geological Survey, Environmental Management Technical Center (EMTC), Onalaska, Wisconsin. We extend special thanks to Robert J. Cosgriff, Illinois Natural History Survey, for compiling GLO survey notes and Janis Ruhser, EMTC, for georeferencing presettlement landcover data.

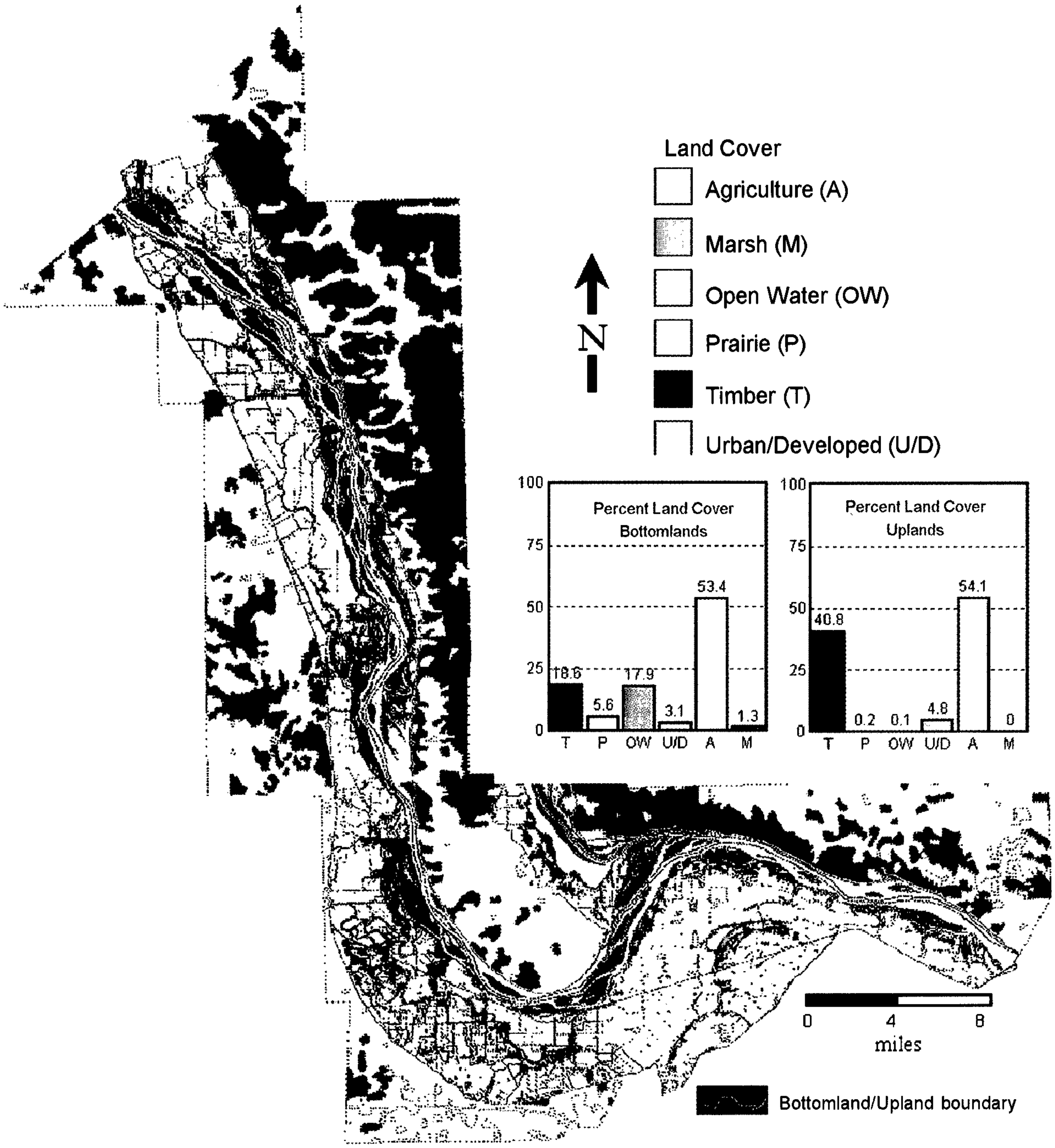

Fig. 7-5. Geographic information system map showing contemporary land cover along navigation reaches 25 and 26 of the upper Mississippi River. Upland landcover data were obtained from the geographic information retrieval and analysis system created by the USGS between the late 1970's and early 1980's at a scale of 1:250,000. Bottomland landcover data were interpreted from 1:15,000-scale color infrared aerial photographs taken in 1989 and 1994. Graphs show percent land cover for timber (T), prairie (P), open water (OW), urban/developed (U/D), agriculture (A), and marsh (M) for the upland and bottomland regions within the study area.

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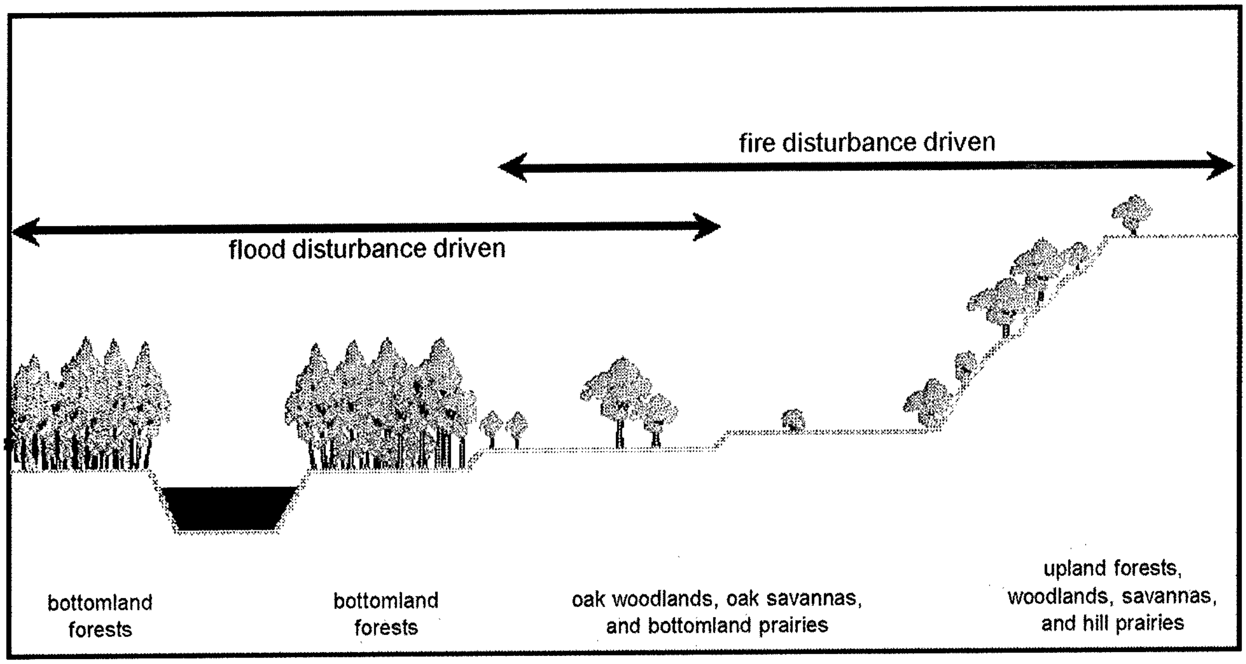

Fig. 7-6. Conceptual model of the presettlement upper Mississippi River valley ecosystem. The bottomlands have many different communities associated with natural levees, meander scars, sloughs, side channels, and lakes. Likewise, the uplands have many different communities associated with rock outcrops, sinkholes, and deep ravines. Degree of flood and/or fire disturbance across bottomland and upland landscapes varied primarily with elevation, but local site factors, such as aspect, soils, and vegetation, were also important.

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Chapter 8: Natural and Human Drivers of Biodiversity in the Greater Yellowstone Ecosystem

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Abstract. Human settlement and land use strongly influence native species in the Greater Yellowstone Ecosystem. This study reconstructs past interactions among ecosystem factors, native species, and human land use to provide a context for future management to sustain both ecological and human communities. Strong gradients in abiotic factors such as topography, climate, and soils appear to cause birds to be abundant and diverse only in localized "hot-spot" settings in the lowlands. Human land allocation and settlement appear to have also been influenced by these abiotic factors, with land use centered around these biodiversity hot spots. Outside of hot-spot habitats, forest management has reduced habitat quality by substituting clearcut logging for natural disturbances such as wildfire. Maintaining native species and human quality of life in the Greater Yellowstone Ecosystem will require coordinated management across public and private lands. Future management should focus on identifying, restoring, and protecting hot-spot habitats while using ecologically based forest management practices in uplands outside of hot spots.

Introduction

The Greater Yellowstone area is one of the largest "intact" ecosystems remaining in the temperate zones of the world (Keiter and Boyce 1991). The vast nature reserves and wildernesses in the Greater Yellowstone Ecosystem (GYE) support a full complement of native birds and mammals, including predators such as grizzly bear and some of the last large herds of migratory ungulates in North America. The GYE offers a unique opportunity to study the role of abiotic factors (e.g., climate and soils) and disturbance (e.g., wildfire) in driving patterns of biodiversity in a "natural" system. At the same time, human development is proceeding rapidly on the private lands surrounding the nature reserves of this ecosystem. Some counties in the GYE have some of the highest human population growth rates in the nation. Thus far, there have been few efforts to quantify where in the GYE landscape humans are settling or the interactions between the human community and the ecosystem. Understanding past interactions between humans and ecosystems provides a context for developing ways to sustain both human and ecological communities in the future.

We are studying natural and human drivers of biodiversity in the northwest portion of the GYE (Fig. 8-1). The objectives of this work are to:

1. Determine the effects of abiotic factors (topography, climate, soils) and natural disturbance on patterns of vegetation and bird diversity.
2. Reconstruct patterns of human land allocation and land use (logging and rural residential development) across the study area from 1850 to present.
3. Evaluate and compare the range of variation in landscape patterns and bird habitats under natural drivers with the range of variation under human drivers.
4. Project vegetation and bird habitat patterns under alternative future management scenarios (present to 2195).

The time periods of interest are 1700-1850 (prior to European human influence), 1850-1940 (initial European settlement), 1940-present (industrial logging and fire suppression), and present-2195 (Fig. 8-2). This paper focuses on objectives and portions of the study area for which analyses are most complete at this time.

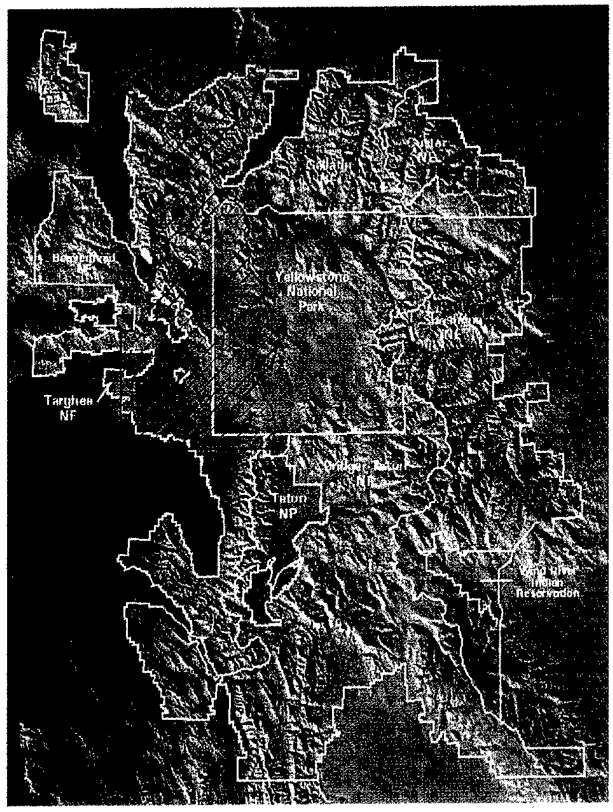

Fig. 8-1. Shaded relief map of the Greater Yellowstone Ecosystem with the study area highlighted (hatched). The study area includes the upper Madison, Gallatin, and Henry's Fork watersheds.

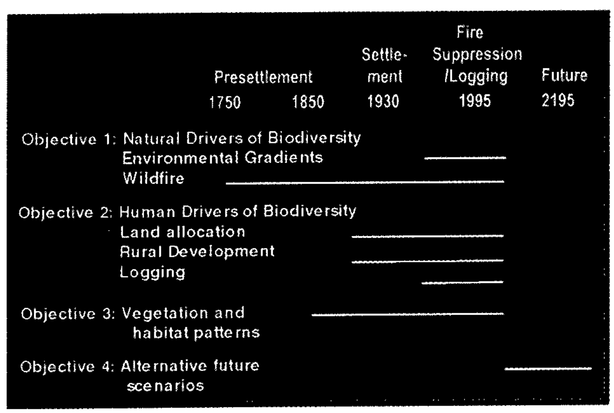

Fig. 8-2. Time periods examined for each of the study objectives.

Abiotic Factors

Most of us think of vegetation composition and structure as strongly driving species diversity in ecosystems such as the Greater Yellowstone. While this is true, it is important not to overlook the importance of topography, climate, and soils to biodiversity (Hansen and Rotella, in press). Such "abiotic factors" are strongly expressed in the GYE, which is really a high mountainous plateau surrounded by lower plains (Fig.8-1). The differences in elevation from the center to the edge of the ecosystem strongly influence climate, with average annual temperatures substantially higher in valley bottoms than at higher elevations (Fig. 8-3). The soils in the valley bottoms are also much richer than those on the Yellowstone Plateau. These gradients in climate and soils influence patterns of vegetation. Lodgepole pine forests cover the poorer, volcanic soils at higher elevations. Douglas fir forests are found in better soils on lower slopes. Aspen, willow, and cottonwood

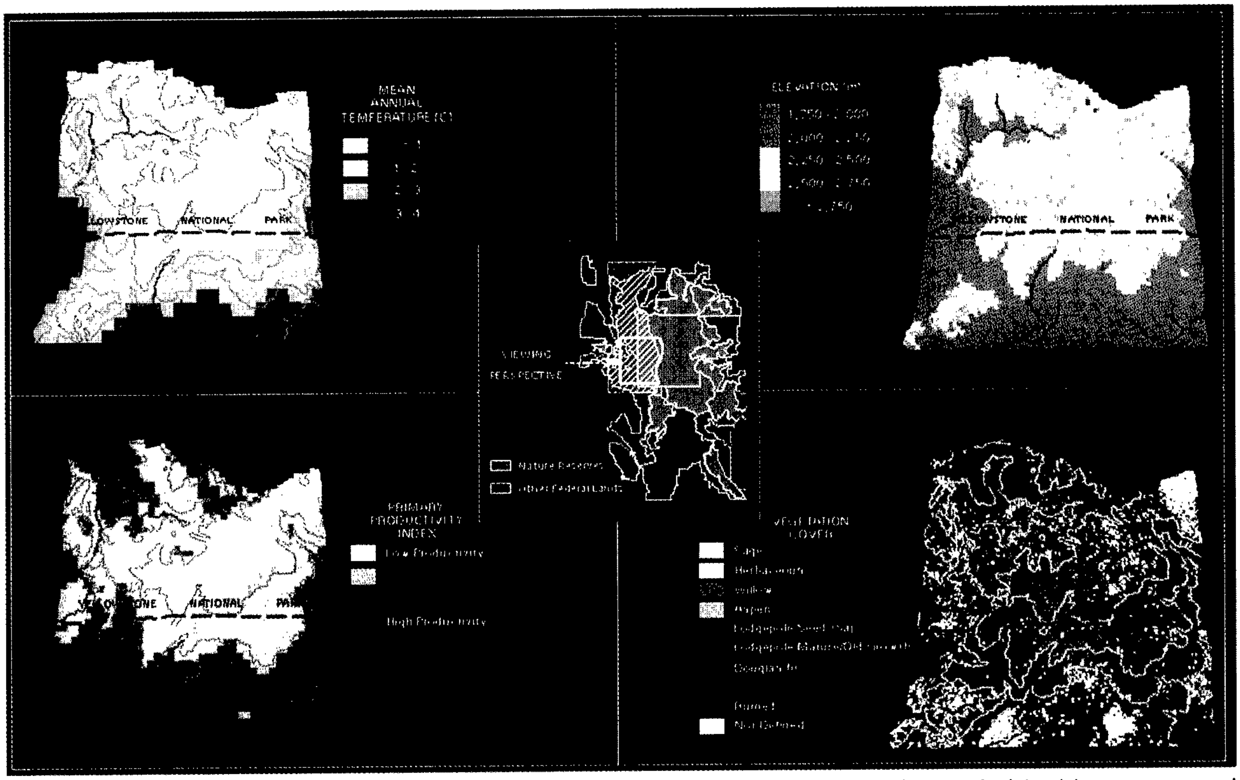

Fig. 8-3. Strong abiotic gradients exist in the GYE. This view of a portion of the current study area depicts: (a) average annual temperature, (b) topography (J. White and S. Running, University of Montana, unpublished data), (c) an index of primary productivity (derived from Normalized Difference Vegetation Index [NDVI] from satellite data; various studies have found correlations between NDVI and net primary productivity, though the key studies have not yet been done in the GYE), and (d) vegetation cover type (derived from Landsat Thematic Mapper imagery).

communities occur on better soils on valley toe slopes and bottoms. These habitats are relatively rare, covering less than 3% of the study area. Environmental gradients also influence plant growth rates. In most years, primary productivity is very low at mid to high elevations on the volcanic soils and is high only in localized settings at lower elevations.

These gradients in climate, soil, and plant productivity strongly influence where native organisms are found. Many bird species are most abundant at lower elevations in habitats where climate is more equitable and primary productivity is highest (Hansen et al., unpublished report). The energy fixed by primary producers cascades through each trophic level in the food chain. Thus, sites high in primary productivity have more energy to support herbivorous, insectivorous, and predatory birds than do sites low in primary productivity. We found that this relationship holds within forest types (e.g., in mature lodgepole pine; Fig. 8-4) as well as among forest types (cottonwood, aspen, and willow communities are higher in net primary productivity and bird abundance and richness than other stand types). Habitats high both in net primary productivity and structural complexity (e.g., number of canopy layers) are "hot spots" for bird abundance and species richness (Fig. 8-5). Notice that these hot spots cover only a small portion of the ecosystem and are mostly at lower elevations. Such settings, however, have also been choice locations for human settlement.

Natural Disturbance

Natural disturbances, especially wildfire, have also left their imprint on the Yellowstone ecosystem. More than 40% of Yellowstone National Park was burned by wildfire in 1988 (Christensen et al. 1989). Driven by the wind, the fire tended to burn in long narrow strips (Fig. 8-6). Elongated islands of forest survived the fire and act as refugia for forest-dwelling organisms. Large fires like this are typical in Yellowstone, recurring about every 200-300 years. Native organisms are well adapted to wildfire. Many plant species recolonized quickly after the fire, and several bird species are dependent upon the habitats created by fire (Fig. 8-7). Vegetation patterns have varied dramatically over

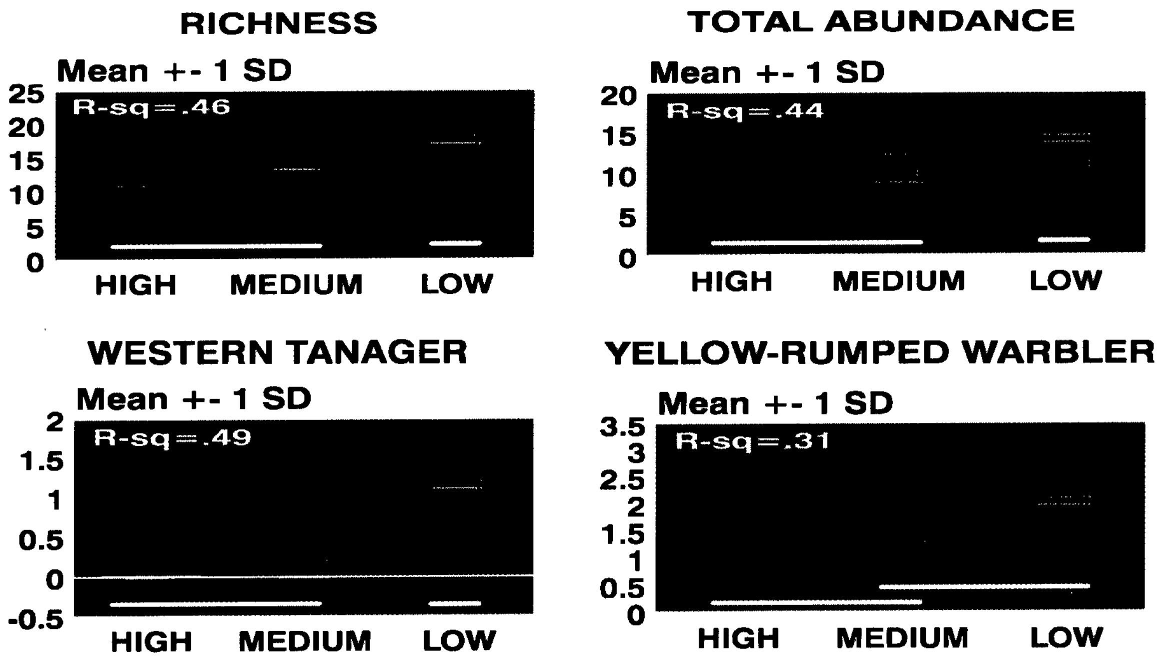

Fig. 8-4. Mean and variation in the abundance of two individual bird species, bird species richness, and total bird abundance across three elevation classes (high > 2500 m; medium 2300-2500 m; low < 2300 m) within mature and old-growth lodgepole pine forests. Elevation classes with nonoverlapping yellow lines differ significantly ($P < 0.05$). We assume that climate and/ or net primary productivity are correlated with elevation, which may explain the results. We are currently analyzing more directly the relationship among bird community attributes, climate, and net primary productivity.

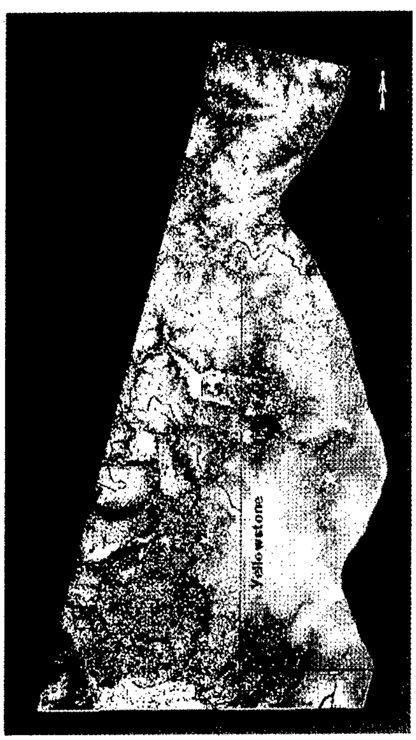

Fig. 8-5. Bird species richness extrapolated from 1995 field data across a portion of the current study area. Increasing richness is indicated from white to red.

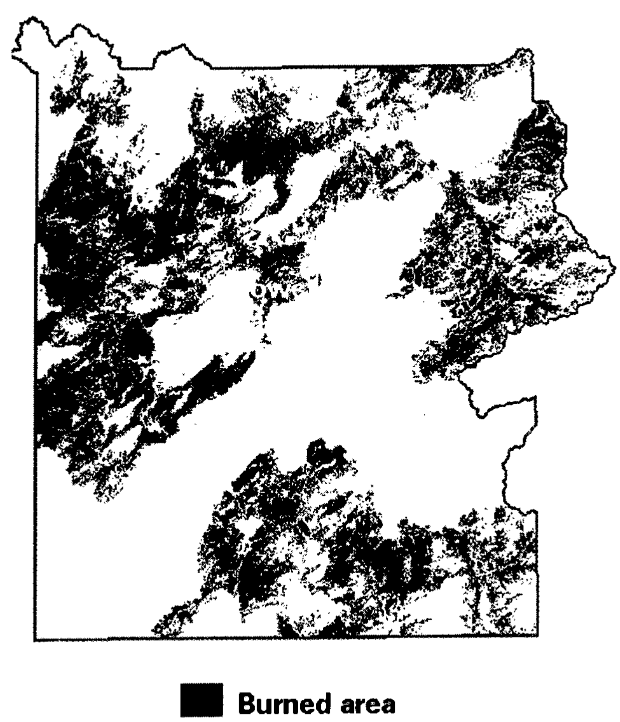

Fig. 8-6. Portions of Yellowstone National Park burned by wildfires in 1988.

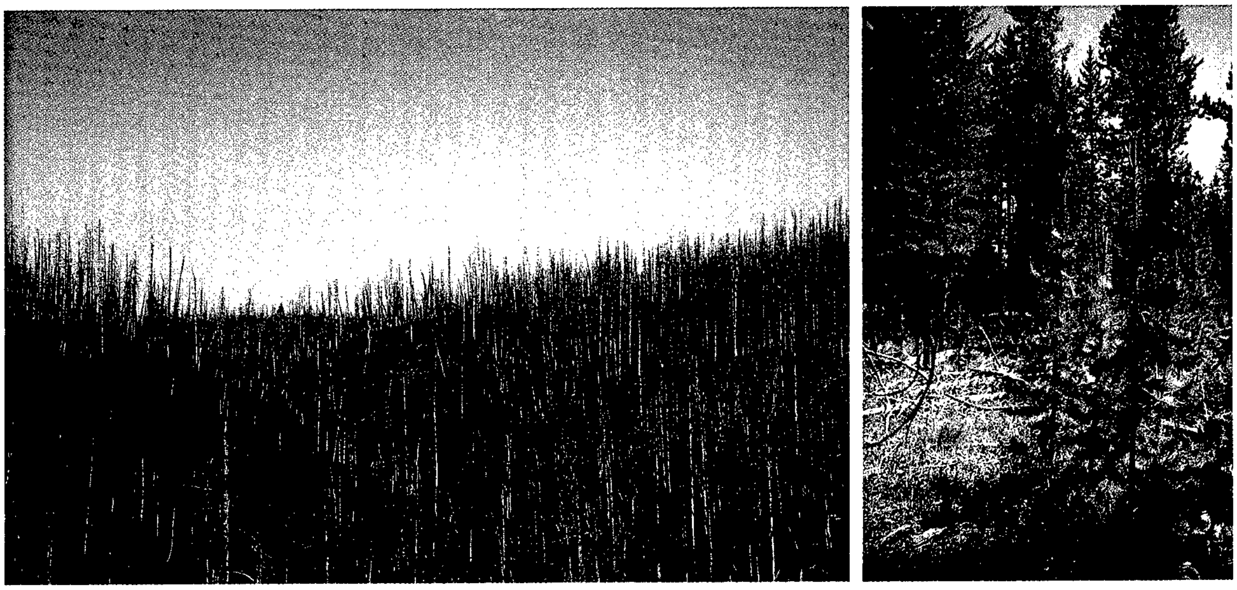

Fig. 8-7. (a) The seedling-sapling successional stage of lodgepole pine forest 8 years after fire. Examples of birds associated with this habitat are black-backed woodpecker, mountain bluebird, and tree swallow. (b) The mature successional stage of lodgepole pine forest that occurs 80-150 years after fire. Typical birds found here include western tanager, ruby-crowned kinglet, and mountain chickadee.

time in this system because of wildfire, creating a dynamic mosaic of habitats and maintaining the full suite of native species (Fig. 8-8).

Human Activities

Land Allocation and Logging

Like birds, people prefer to occupy certain places in the landscape, and current land allocation reflects this tendency. Homesteaders tended to choose lands at low elevations, on productive soils, and near streams (Fig. 8-9), and private lands continue to occupy these settings. Nature reserves (e.g., Yellowstone National Park, Lee Metcalf Wilderness) were placed at the highest elevations in the less productive sites (Fig. 8-10). Extractive federal lands (e.g., national forests) surround these nature reserves.

Human land use tends to increase in intensity at lower elevations. Logging on the Targhee National Forest initially occurred at the lowest elevations and gradually worked up to the Yellowstone National Park boundary. These patterns of land allocation and land use suggest that human activities are concentrated in low-elevation, productive landscape settings that are also important hot spots for native species.

Some land-use practices such as clearcut logging produce vegetation patterns that differ dramatically from those created by wildfire. Compared to clearcutting, wildfire leaves many standing and downed dead trees, scattered live trees, and understory plants that hasten recovery after the fire. Wildfire patches are also more variable in size and shape

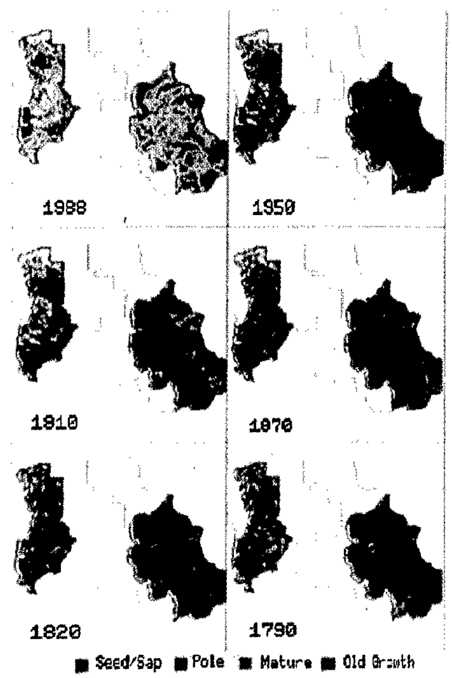

Fig. 8-8. Past vegetation patterns in two portions of the Targhee National Forest under the influence of wildfire (before 1950) and logging (after 1950). The computer model PAYSAGE (Hansen et al. 1996) was used to backdate vegetation based on current stand age and successional sequence. During some time periods the landscape was dominated by seedling and sapling seral stages resulting from wildfire and logging. At other time periods, the landscape was dominated by mature and old-growth forest (from Patten and Hansen 1995).

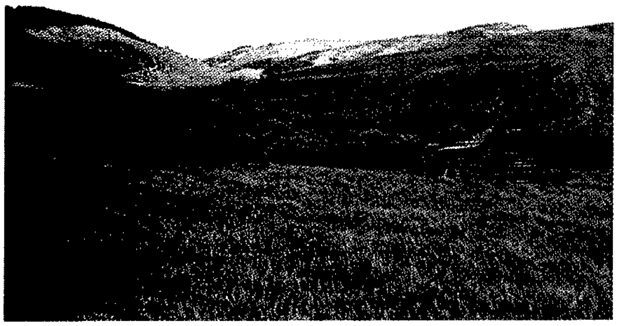

Fig. 8-9. Remains of a homestead on a productive valley bottom near the Gallatin River.

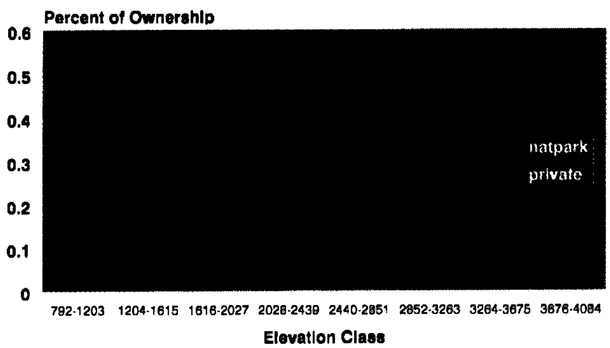

Fig. 8-10. Frequency distribution of land allocation across elevation classes over the study area. Note that nature reserves (natpark) tend to occur at high elevations while most private lands are at lower elevations.

than clearcuts and the remaining forest is less fragmented under wildfire than logging (Fig. 8-11). Because of these differences, wildfire tends to maintain ecological processes and native organisms much better than clearcut logging.

Such comparisons of natural disturbance and human activities are helpful for managing future landscapes. Some ecologists have suggested that we can best achieve ecological objectives by mimicking the patterns and processes that were typical in these landscapes prior to modern human influences. The underlying assumption of this approach is that ecological processes and native organisms persisted through the Holocene and should continue if future landscapes are maintained within the range of variation typical of presettlement times. This approach is relatively new and questions remain about its feasibility and effectiveness. For example, the presettlement range of variation in vegetation cover type for a fire-driven system like the GYE is very broad (e.g., Fig. 8-8). Simply maintaining modern landscapes somewhere within this wide range may not accomplish ecological objectives. Attention to changes in spatial patterning over time is also needed. Moreover, it is likely socially unacceptable to maintain large disturbances in modern landscapes.

An alternative approach is to use an understanding of the interactions between ecosystems and human land use to design landscapes to accomplish management objectives. For example, knowledge of environmental gradients, natural disturbance, and human activities described here could be used to tailor management strategies to sustain both ecological and human communities (e.g., Hansen and Rotella, in press). In the case of the GYE, the challenge is to integrate management of natural disturbance and land use across public and private lands so as to maintain suitable habitats for native species across the full elevational gradient.

Rural Residential Development

Land use tends to shift from timber management to grazing, agriculture, rural residential, and urban as we move down in elevation from the Yellowstone Plateau to the Gallatin Valley (Fig. 8-12). A wave of "urban refugees" is emigrating to the Northern Rockies from across the United States, fueling subdivision of seminatural lands (Fig. 8-13, 8-14).

This human development may be influencing native biodiversity even more than previously expected. Our initial analyses suggest that grazing, agriculture, and rural residential development tend to focus on the locations and habitats that are high in net primary productivity and that may be hot spots for native species (Fig. 8-15). About 25% of the bird species we sampled were strongly associated with hot-spot habitats. Hot spots may also be very important to species that also use other habitats. Reproduction and survival may be especially high in hot-spot habitats, allowing these areas to serve as population source areas, producing abundant offspring that disperse widely and are critical for maintaining the viability of many plant and animal populations across the region. Our initial studies indicate, however, that birds in hot spots near human activity have low reproductive rates due to nest predators that are abundant in human landscapes (e.g., raccoons). Thus, human activities in and around biodiversity hot spots may reduce habitat quality and population viability for native species.

Implications for Ecosystem Management

These results suggest that human settlement and intense land use are centered on just the locations in the landscape that are most important to native species. Gradients in topography, climate, and soils result in hot spots for native species in localized settings in the lowlands. Many of the new immigrants to the GYE are attracted to these same localities, concentrating private lands, human settlement, and intense land use in the productive lowlands. Given this overlap, human impacts on biodiversity

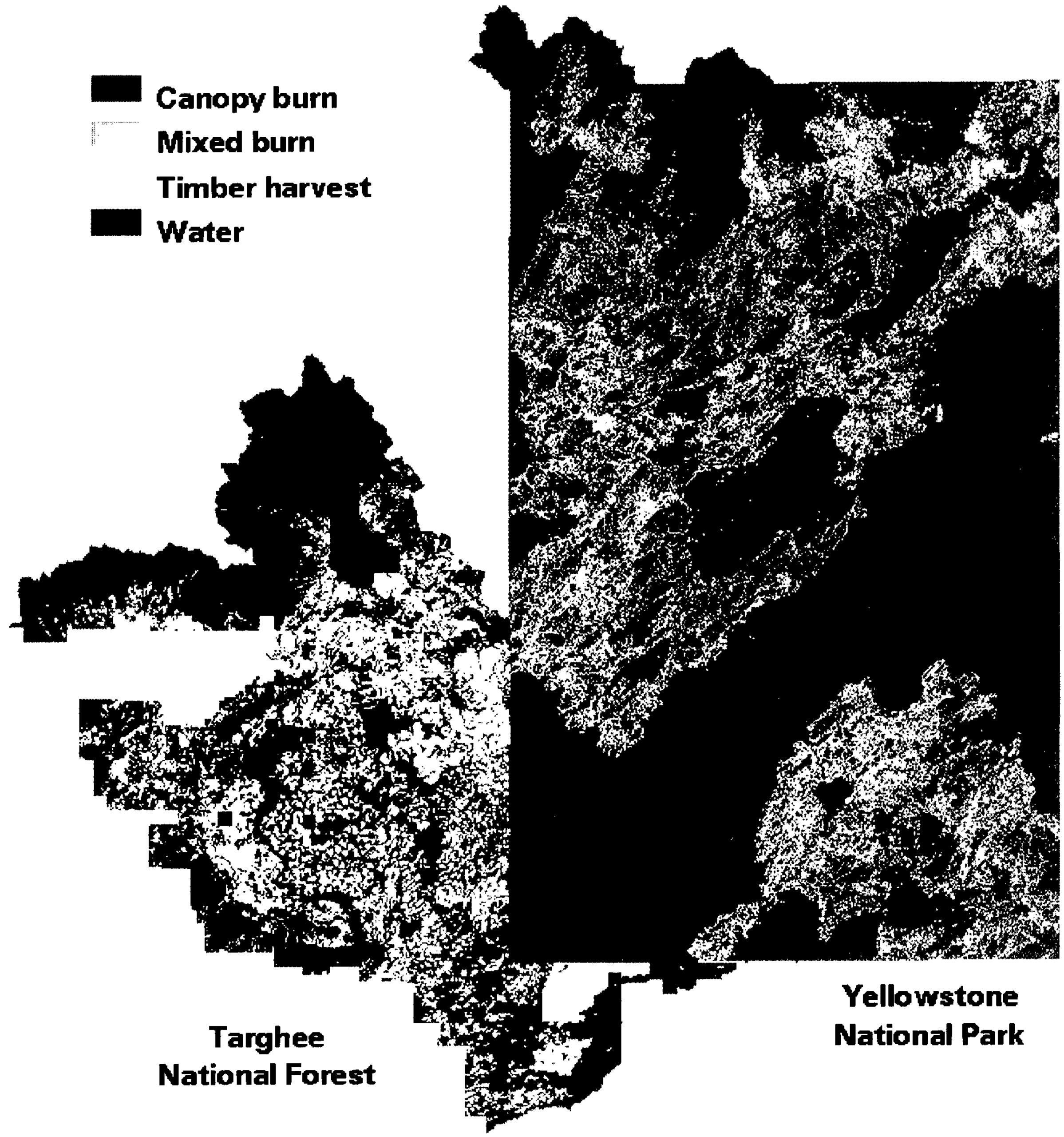

Fig. 8-11. Landscape patterns imposed by wildfire (1988) in Yellowstone National Park and by clearcut logging (1950-90) in the Targhee National Forest.

and ecological processes may be greater than would be predicted based on human population density alone. Knowledge of the relationships between abiotic factors, natural disturbance, biodiversity, and human land use is critical for deriving management strategies to sustain both native species and human communities.

Our results suggest that it is important to identify biodiversity hot spots in the GYE and to design conservation plans to protect them from land development. Conservation easements and land acquisition may be effective means of preserving hot-spot habitats that are now on private lands. It is also important to identify the environmental factors that cause variation in species abundance and richness so that management plans can be designed to maintain and improve the conditions required by species of concern. Further mapping of abiotic factors, natural

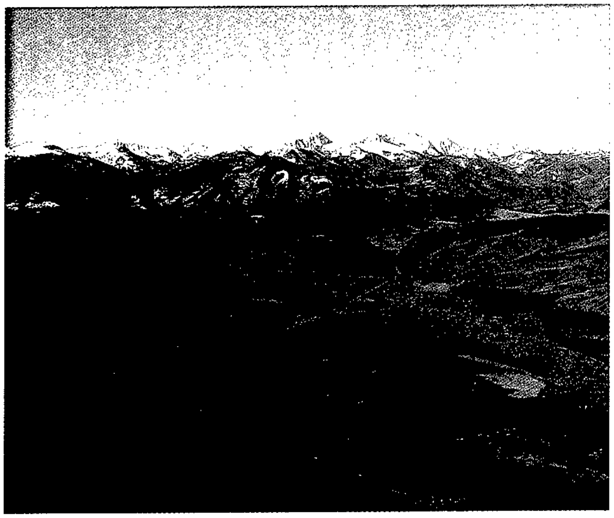

Fig. 8-12. The Gallatin Valley near Bozeman, Montana, looking south towards Yellowstone National Park.

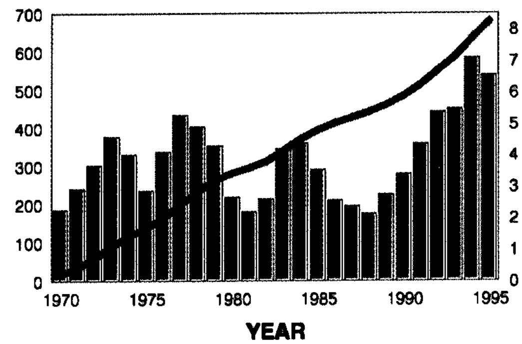

Fig. 8-14. New construction in Gallatin County, Montana, 1979-95, as evidenced by septic permits (expressed as number per year and cumulative number since 1970). Notice that rates of development have increased dramatically since 1990.

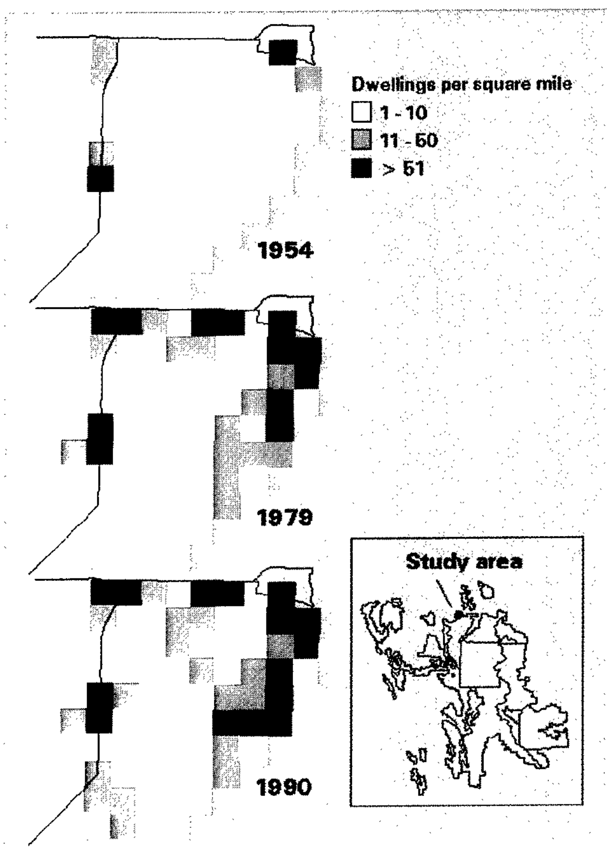

Fig. 8-13. Change in rural residential development in a portion of Gallatin County, Montana, from 1954 to 1990. The city of Bozeman is in the upper right of each panel. The most rapid development occurred along transportation routes, near streams, and in foothills with attractive scenery.

disturbance, native species, and human land use across this ecosystem is needed to identify previously unknown hot spots. Beyond preserving hot spots, active restoration will be required in some locations. Restoration may be accomplished by reintroducing natural disturbances such as fire or flooding to restart vegetation succession, using silvicultural strategies to restore the structural complexity of vegetation, and restricting livestock densities and home placement near some biodiversity hot spots.

Outside of hot spots, management should strive to maintain the quality of habitats for native species. Timber harvest regimes should be designed to create the structural complexity and landscape patterns typical of natural disturbances such as wildfire. Rather than simply mimicking presettlement disturbances, the challenge is to manage the spatial scale, location, and frequency of disturbance so as to best maintain the full suite of habitats for native species.

Accomplishing these management objectives will require a new level of cooperation among government agencies, private land owners, and local governments. Clearly, the GYE is a complex and tightly linked ecosystem. Understanding and managing the strong linkages between biodiversity and socioeconomic forces here can help to maintain the current high quality of life for humans in this region.

Acknowledgments

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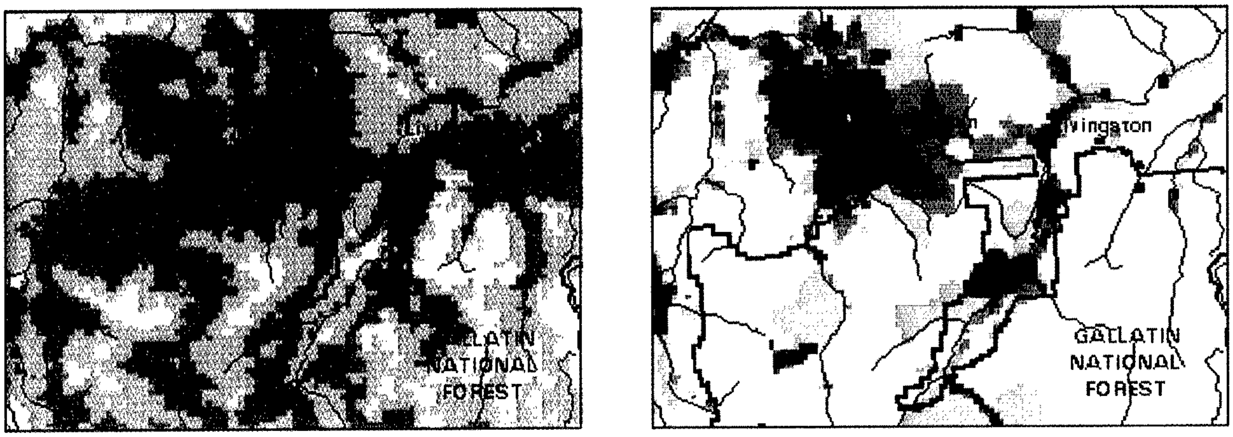

RELATIVE NET PRIMARY PRODUCTIVITY   RELATIVE HUMAN POPULATION DENSITY

Fig. 8-15. Potential hot spots for ecological processes and biodiversity also may be strongly correlated with locations of intense human land use. Here, primary productivity (estimated from NDVI-tranformed AVHRR data) is compared with human population density (1990 data). NDVI is correlated with primary productivity, though the exact relationship is not yet known for this area. For both images, low to high values correspond with light to dark shades, respectively.

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Chapter 9:
Landscape Changes in the Southwestern United States: Techniques, Long-term Data Sets, and Trends

by

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Abstract. The great ecological diversity of landscapes in the American Southwest results from combinations of the underlying patterns of topographic complexity, climatic variability, and environmental histories. This chapter illustrates some high-resolution and long-term data sets and approaches for reconstructing landscape change in the Southwest, including the paleobotanical record, repeat photography, and fire-scar histories from tree rings. We explore the effectiveness of collecting historical data at multiple locations to build networks that allow analyses to be scaled up from localities to regions and the use of historical data to discriminate between natural and cultural causes of environmental change.

Introduction

The American Southwest is a region where great ecological diversity is maintained by topographic complexity and extreme variability in climate. Despite the pervasive influence of livestock grazing and other human land uses in the Southwest, natural vegetation predominates over vast tracts of public land. Because natural processes are still very much in play, human impacts in this region are seldom "clearly" evident. In fact, the greatest challenge in assembling and interpreting a land-use history of the Southwest is disentangling cultural from natural causes of environmental change. We have employed a variety of tools, techniques, and data types to address this challenge.

Here we illustrate some historical and paleoecological perspectives on environmental change in the Southwest. Among the themes we explore are:

1. The importance of climatic variability in driving ecological processes, as well as in modulating human land uses and their effects on southwestern landscapes.
2. The use of historical and paleoecological data to detect and explain trends in ecological patterns and processes across southwestern landscapes.

3. The effectiveness of network approaches in the development of historical data sets. By aggregating data spatially, observations and inferences can be scaled up from localities to landscapes and regions.
4. The use of historical data to discriminate between natural and cultural causes of environmental change.
5. The use of historical data to define and constrain natural ranges of variability and, in some cases, to set targets or determine templates for restoration and sustainable use of ecosystems.

This chapter illustrates some approaches for reconstructing landscape change in the Southwest from high-resolution and long-term data sets including the paleobotanical record, repeat photography, and fire-scar histories from tree rings.

Methods

The Paleobotanical Record

An important backdrop for evaluating human impacts on southwestern landscapes is the long-term dynamics of vegetation change. Glacial climatic and vegetation patterns have characterized most of the Pleistocene (the past 1.2 million years). Just 12,000 years ago, the Earth underwent major environmental changes in the transition to the current interglacial period, the Holocene. Dramatic swings in atmospheric chemistry and climate, as well as global ice volumes and sea level, caused massive shifts in biotic distributions. Vegetation change in humid areas has been reconstructed from analysis of pollen grains preserved in lake sediments, but opportunities for pollen analysis are limited in arid regions due to scarcity of persistent water bodies, low proportion of wind-pollinated plant species, and poor pollen preservation in alkaline sediments. In the arid interior of North America, a novel way of reconstructing vegetation change has been the analysis of plant and animal remains preserved in fossil packrat (*Neotoma* spp.) middens, deposits that are ubiquitous in rocky environments. About the size of a laboratory rat, packrats gather nearby plant materials (within 100 m at most) and accumulate them in dry caves and crevices; there, the plant and other debris (including arthropod and vertebrate remains) are cemented into large masses of crystallized urine (referred to as amberat), which can persevere for tens of thousands of years. About 2,500 of these deposits have been dated within the limit of the radiocarbon method (the last 50,000 years) and analyzed for plant and animal remains (Betancourt et al. 1990). The preservation of plant remains in packrat middens is excellent, allowing identification of species and diverse morphological, geochemical, and genetic analyses (e.g., Van de Water et al. 1994; Smith et al. 1995). The extensive archive of sorted, identified, and dated material represents the richest and best-documented source of plant remains in the world, with hundreds of species identified and available for corollary studies. Maps of modern versus Pleistocene vegetation in the Southwest imply remarkable changes during the last 12,000 years (Fig. 9-1); plant migrations initiated during the Holocene may still be ongoing and hence complicate simple cultural versus natural explanations of vegetation change (Figs. 9-2 and 9-3).

Repeat Photography

Ground-Based Photography

Historical photographs of key landscapes, from hillslopes to wetlands, are available for practically any area of the western United States (Rogers et al. 1984). As a first approximation, past environmental change can be measured by finding the site of a historical photograph, reoccupying the original camera position, and making a new photograph of the same scene. Differences between then and now provide a basis for identifying and even quantifying changes, while the new photograph establishes a benchmark for future evaluation. Repeat photography is a simple, inexpensive, and elegant tool for reconstructing past environmental changes and monitoring future ones; it is particularly well suited for the relatively open landscapes of the western United States (Hastings and Turner 1965; Rogers 1982; Veblen and Lorenz 1991; Webb 1996). Repeat photography in the Southwest has focused on key ecological concerns relevant to management of public lands, including shrub and tree encroachment upon grasslands (Figs. 9-4 and 9-5), climatic effects on demographic trends in woodlands, postdisturbance histories, and geomorphic, hydrologic, and vegetation changes in riparian areas (Figs. 9-6 and 9-7).

In the Southwest, the process of desertification has involved expansion of desert shrubs and trees into former grasslands (Figs. 9-4 and 9-5). Shrub encroachment is difficult to reverse because nutrients and other resources quickly begin to accumulate underneath shrubs, creating resource islands that discourage grassland recovery (Schlesinger et al. 1990). Explanations for shrub encroachment have ranged from fire suppression and livestock grazing (Grover and Musick 1990) to interdecadal climatic variability (Neilson 1986) and, most recently, to CO_2 enrichment shifting the balance from warm-season grasses to cool-season shrubs (Idso 1992). The debate is confounded by the fact that progressive range deterioration since 1870 has been inferred from historical data (Bahre and Shelton 1993), while long-term monitoring indicates substantial range improvement with wetter conditions following the drought of the 1950's (McCormick and Galt 1994).

One of the most remarkable changes in southwestern landscapes involved late nineteenth and early twentieth century channel entrenchment (Fig. 9-6). Between 1865 and 1915, arroyos developed in alluvial valleys of the southwestern United States across a wide variety of hydrological, ecological, and cultural settings. That they developed more or less simultaneously has encouraged the search for

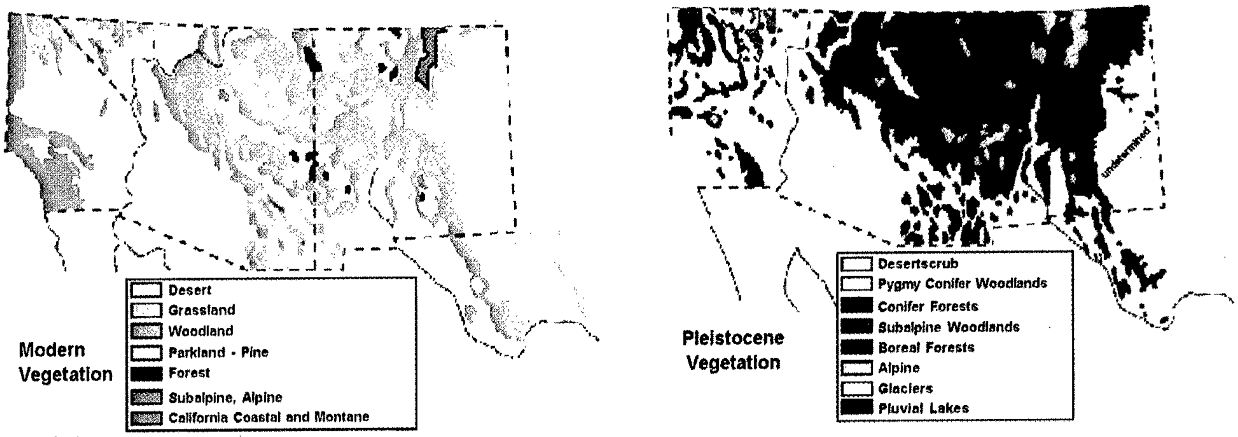

Fig. 9-1. As this comparison of modern and Pleistocene vegetation shows, southwestern landscapes have changed dramatically since the end of the last ice age, 12,000 years ago. During the last ice age, desert vegetation was restricted to the lower elevations (<300 m) in Death Valley and the mouth of the Colorado River. Hallmarks of the Sonoran Desert, such as the giant saguaro cactus (*Carnegiea gigantea*) and the palo verde (*Cercidium* sp.), were displaced far south into Mexico. Creosotebush (*Larrea tridentata*), the dominant shrub of the Chihuahuan, Sonoran, and Mojave deserts, had its northernmost populations along the Arizona-Sonora border. Extensive pinyon-juniper-oak woodlands, now restricted to the highlands, covered what are now desert elevations (300-1700 m). The extensiveness of spruce-fir, mixed-conifer, or subalpine forests and woodlands during glacial times is evident in their coverage over much the same territory as modern pinyon-juniper woodlands, currently the third largest vegetation type in the United States (20 million ha). The biggest surprise from the packrat midden record is the virtual absence of ponderosa pine (*Pinus ponderosa*), a tree that today extends from central Mexico along the axis of the Rockies into Canada. In the United States, much of that range developed through migration during the last 10,000 years. Populations of this commercial species in the northern Rockies and western High Plains may represent arrivals within the last few millennia and perhaps the last few centuries.

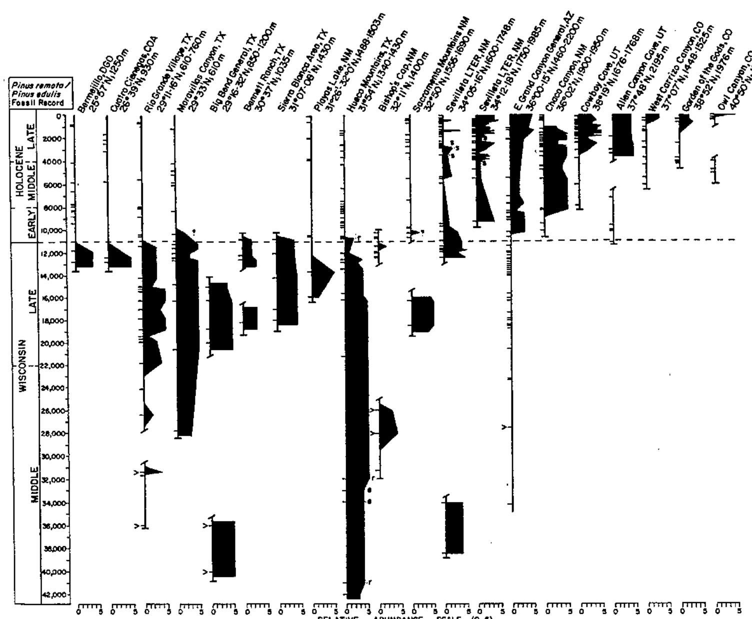

Fig. 9-2. Diagram showing fossil packrat midden records with papershell pinyon (*Pinus remota*, south of the Hueco Mountains near El Paso), and Colorado pinyon (*Pinus edulis*, north of Hueco Mountains) during radiocarbon time for the last 40,000 years. The tickmarks on each vertical line represent over 350 radiocarbon-dated middens that show the presence or absence of pinyon pines along a 15° latitude (ca. 1,00 km) transect from Bermejillo, Mexico (Durango Province), to Fort Collins, Colorado. The diagram depicts the local extinction of pinyon populations growing in the Chihuahuan Desert during the last deglaciation (around 11,000 radiocarbon years ago) and the sequential migration to higher elevations and more northerly latitudes during the Holocene (the last 11,000 years). Note that Colorado pinyon's distribution in the state of Colorado may be just a few hundred years old and probably is not yet in equilibrium with modern climate. In Colorado and northern New Mexico, this recent migration makes it difficult to discriminate the last phases of Holocene migration from historical tree expansion due to fire suppression and overgrazing.

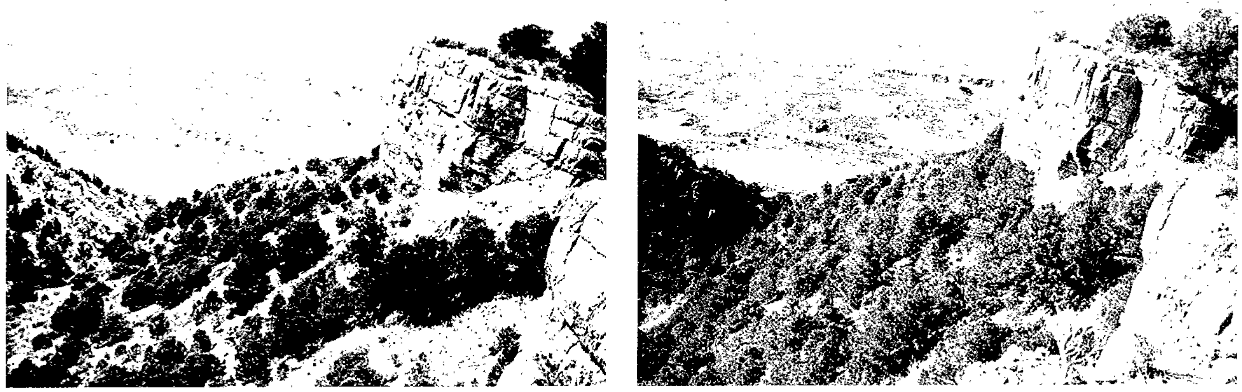

Fig. 9-3. An isolated stand of Colorado pinyon (*Pinus edulis*) at Owl Canyon, north of Fort Collins, Colorado, represents the endpoint of its northward migration since the end of the last ice age (Betancourt et al. 1991). This 5 km ^{2} stand was colonized by pinyon pine less than 500 years ago, possibly from accidental plantings by Cheyenne and Arapaho, who carried pinyon nuts in their "trail mix" on treks along the Front Range. The nearest potential source populations are 250 km to the south near Colorado Springs. It is unclear what role humans played in movement of seeds and plant migration during the Holocene. Note the rapid increase in canopy cover from 1950 to 1989, characteristic of an expanding population. (Photos: 1950, J.D. Wright; 1989, R.M. Turner.)

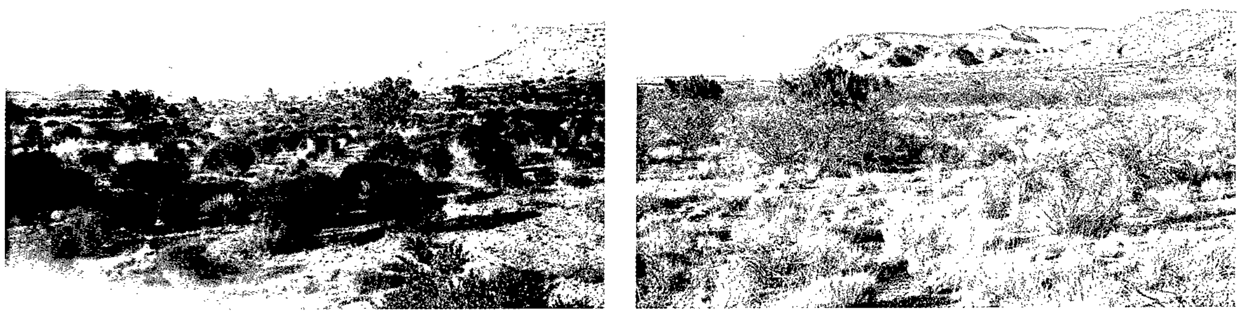

Fig. 9-4. Creosotebush (*Larrea tridentata*) arrived at the Sevilleta Long-Term Ecological Research site south of Albuquerque about 2,500 years ago and expanded into what was once open grassland during the twentieth century, as shown in photographs from July 1915 and August 1989. The site of the photograph was open grassland when the Spanish began grazing sheep and cattle in the 1700's, but this grassland was invaded by snakeweed (*Gutierrezia sarothrae*) and later by creosotebush (*Larrea tridentata*). Note the lone creosotebush at the right foreground and the beachball-sized snakeweed throughout the foreground of the 1915 photograph. This photograph was taken after one of the wettest years in New Mexico history. By the time of the 1989 photograph, creosotebush had expanded throughout this former grassland, with the invasion accelerated during an extended drought between 1942 and 1972 (Betancourt et al. 1993). Also note the increase in one-seed juniper (*Juniperus monosperma*) on the slopes in the right background. (Photos: 1915, N.H. Darton; 1989, R.M. Turner and J.L. Betancourt.)

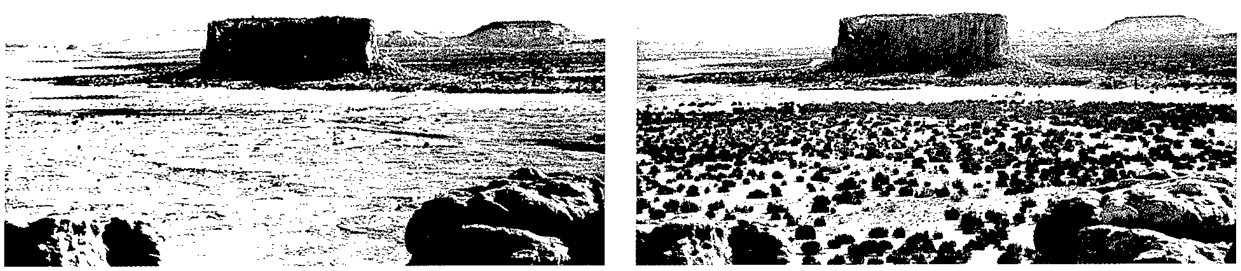

Fig. 9-5. Views from Acoma Pueblo to Enchanted Mesa, 100 km west of Albuquerque, in 1899 and 1977. Note expansion of junipers (*Juniperus monosperma*) between 1899 and 1977. In many parts of the west, juniper expansion has been blamed on fire suppression and livestock grazing, justifying an aggressive program of chaining and burning pinyon-juniper woodlands in the 1960's and 1970's to improve forage and water yield. Several authors have suggested that pinyon-juniper expansion may instead represent recovery from prehistoric fuel harvesting, at least in those areas that were heavily populated within the last 1,000 years (Samuels and Betancourt 1982; Kohler 1988). One such place could be Acoma Pueblo. (Photos: 1899, W.H. Jackson; 1977, H.E. Malde.)

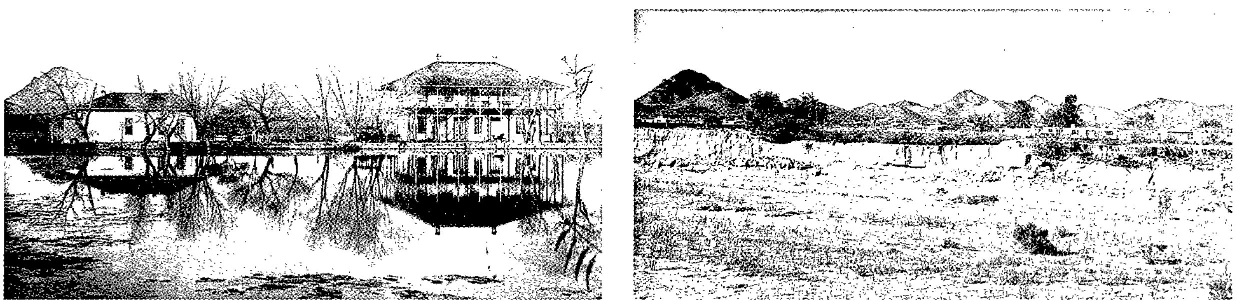

Fig. 9-6. In July and August of 1890, heavy flooding cut a deep channel in the Santa Cruz River at Tucson. As arroyo cutting progressed, it ultimately destroyed nearby Silver Lake, an impoundment on the Santa Cruz River which powered the waterwheels of local flour mills and provided irrigation water for agricultural lands downstream. Compare these photographs of Silver Lake in 1891 and 1982 (Betancourt and Turner 1988). (Photos: 1891, unknown; 1982, R.M. Turner and J.L. Betancourt.)

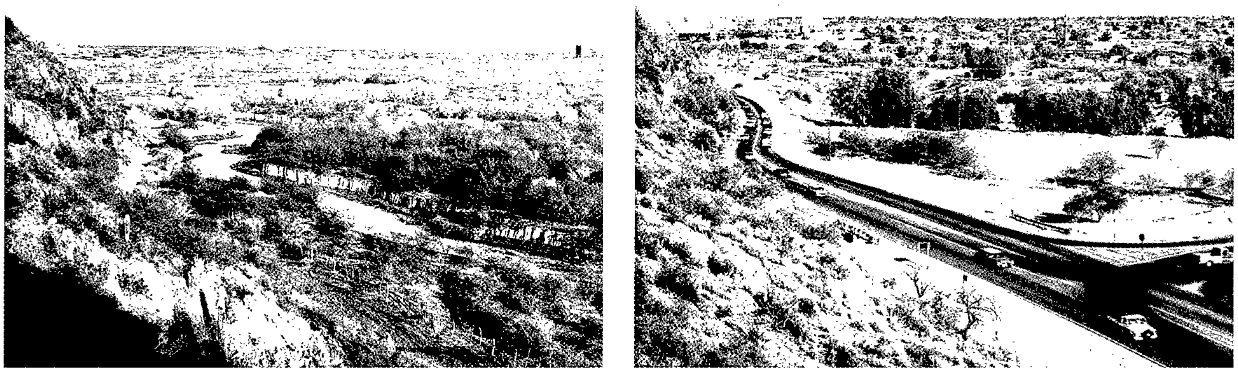

Fig.9-7. Downstream view of the confluence of the west branch of the Santa Cruz River in Tucson, looking northeast from the lower slope of Sentinel Peak. Between 1904 and 1981 deterioration of the riparian vegetation is evident due to groundwater depletion and urbanization, along with arroyo cutting. Many other southwestern floodplains have undergone similar changes, including reaches of the Rio Grande, the Salt River, and the Gila River. (Photos: 1904, unknown; 1981, R.M. Turner and J.L. Betancourt.)

a common cause, some phenomenon that was equally widespread and synchronous. As with most recent environmental changes, whether global or local, efforts to understand arroyo genesis have been hindered by the inability to discriminate between natural and cultural factors. Much debate has focused on the regional and local causes for historic arroyo-cutting (Bull 1997). Range managers have been quick to point to the removal of plant cover by livestock, whereas climatologists have naturally looked to the skies for an explanation. The geologist, accustomed to studying the products of erosion over long periods of time, sees arroyos as symptomatic of inherent instability in arid landscapes, while acknowledging that geomorphic thresholds may be exceeded with changes in climate and vegetation. Following arroyo initiation, two of the more pervasive impacts on southwestern watersheds have been deterioration of wetlands and degradation of streamside vegetation, caused by groundwater withdrawal and urbanization (Fig. 9-7).

Aerial Photography

Aerial photography and other remote sensing approaches (e.g., satellite imagery) provide powerful means of determining widespread changes in landscape patterns through time, especially when used in concert with geographic information systems (Sample 1994). Aerial photography was performed across most of the Southwest in the mid-1930's, providing a baseline from which modern landscape changes can be assessed (Allen and Breshears 1998).

Groundbased evidence, such as tree ages and soil patterns, indicate that conifer trees have widely invaded ancient montane grasslands in the Jemez Mountains of northern New Mexico during this century (Allen 1989). Aerial photographs confirm these observations and reveal the extensiveness of the tree encroachment (Fig. 9-8), which reduced the area of open montane grasslands by 55% between 1935 and 1981 across the 100,000 ha mapped area. The tree invasion has been tied to changes in land-use

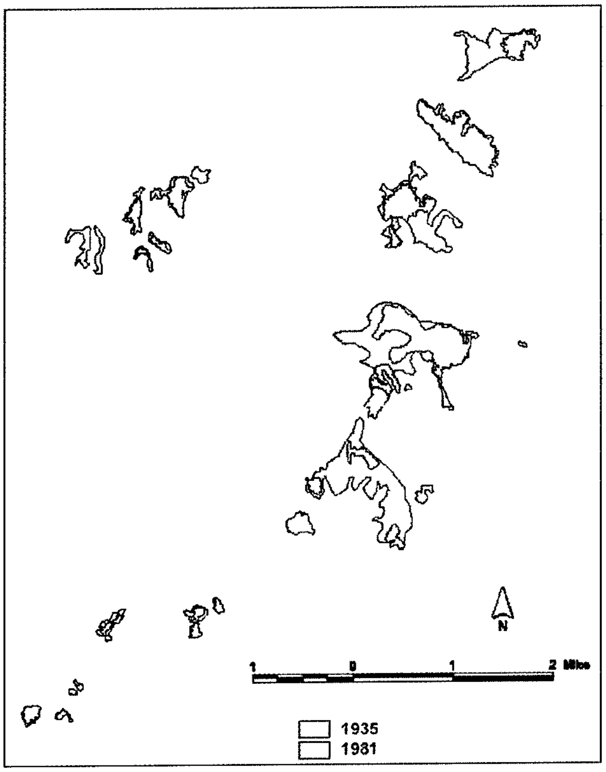

Fig. 9-8. Map of changes in montane grassland area between 1935 and 1981 in the southeastern Jemez Mountains, New Mexico. Area of open grassland (with less than 10% tree canopy cover) was determined from aerial photographs.

history, primarily livestock grazing and fire suppression (Allen 1989).

Changes in road networks through time reflect and determine land use histories, as illustrated in this Jemez Mountains example. Total road density in 1935 (Fig. 9-9) was greatest on the homesteaded lands just north of Bandelier National Monument, where dirt and primitive roads provided access to agricultural fields, dwellings, and timber and fuelwood resources. West of Bandelier National Monument, roads provided access to ranches, mines, and some timber operations. Large portions of the Jemez area remained roadless.

In 1935 the Denver and Rio Grande Railroad was still in operation through the eastern edge of the map area. Completed between 1880 and 1886, this important connection between the Jemez Mountains and the outside world markedly altered land use patterns in this area (Rothman 1992). The improved linkages to outside markets provided by railroads throughout the Southwest in the late 1800's allowed the concurrent, region-wide buildup of extreme numbers of livestock (Wooton 1908), which precipitated key landscape changes such as vegetation transformations and altered fire regimes.

By 1981 (Fig. 9-9) the length of mapped roads increased nearly twelvefold, from 719 km in 1935 to 8,433 km (Allen

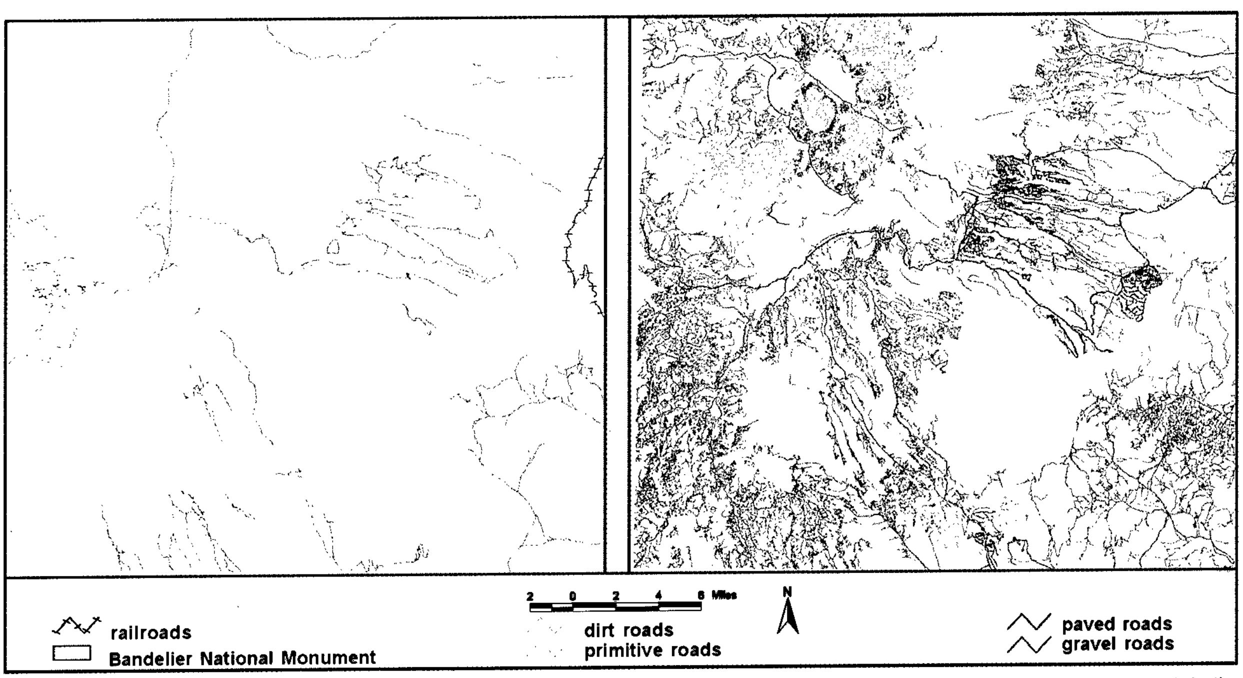

Fig. 9-9. Map of all roads visible in 1935 and 1981 aerial photographs across 187,858 ha around Bandelier National Monument, in the Jemez Mountains, New Mexico. The current national monument boundaries are shown. "Dirt" roads have a bulldozed surface, while "primitive" is a variable category that includes logging skid trails, informal woodcutting tracks, some powerline corridors, and off-road vehicle paths.

1989). The pattern of paved roads north of Bandelier reflects intensive human development activities, as the agricultural homesteads turned into the industrialized technical areas of Los Alamos National Laboratory, with its associated townsites of Los Alamos and White Rock. The dense networks of dirt and primitive roads to the west of Bandelier were created by a variety of logging activities on public and private lands during the 1960's and 1970's (e.g., the striking spiral patterns of dirt roads observed in the northwest quadrant of Fig. 9-9). The largest remaining roadless tract was the designated wilderness areas in and adjoining Bandelier National Monument. Estimated total area of road surfaces grew from 0.13% of the map area in 1935 (247 ha) to 1.67% in 1981 (3,132 ha). These estimates of road surface areas do not include shoulders, cut and fill slopes, or ditches, and thus are conservative estimates of landscape area directly altered by roads.

The great increase in road networks observed since 1935 in the Jemez Mountains suggests the possibility of significant, landscape-wide ecological impacts (Allen 1989). The U.S. Forest Service has recently recognized the existence of over 690,000 km of national-forest roads on its lands across the United States (see details at http://www.fs.fed.us/news/roads), highlighting the magnitude of wildland road networks in this country. Roads can have many ecological effects, ranging from habitat fragmentation and reduced landscape productivity to the direct conversion of roadways into compacted and sparsely vegetated surfaces. They can also provide routes for the spread of nonnative weeds, accelerate erosion rates, and increase stream sediment loads. Roads act as fire breaks and facilitate extensive access to formerly remote areas for fire suppression. Roads also allow increased human access for recreational and consumptive purposes, resulting in widespread habitat modifications (e.g., cutting of snags for fuelwood) and disturbances to wildlife (e.g., through vehicle traffic and hunting) that alter biotic communities. Overall, road networks often provide distinctive landscape signatures of the histories and ecological effects of human land uses.

Fire-Scar Histories

Well-dated fire-scar chronologies aggregated over space and time provide powerful, multiscale perspectives of the variability of past fire regimes (Figs. 9-10 and 9-11). These fire-scar chronologies document a history of frequent, widespread surface fires in many southwestern forest types (Swetnam and Baisan 1996; Fig. 9-12). Fire is a "keystone process" (see Holling 1992) in the Southwest, and patterns of change in the fire-scar record are interpretable in the context of climatic variation and changes in land use and forest stand structures (including fuel conditions). Thus, fire histories record the ecological "pulse" of southwestern forests, integrating both natural and cultural histories.

Regional fire years (Fig. 9-12) were an episodic phenomena in southwestern forests, and the synchronized nature

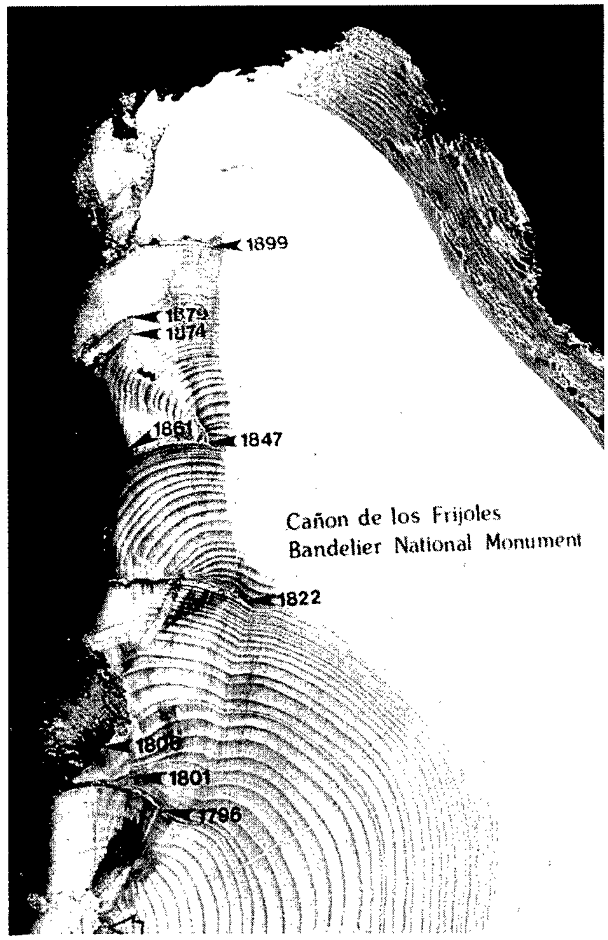

Fig. 9-10. Repeated surface fires cause a sequence of overlapping wounds. The heat-killed wood tissues extend into the annual rings, which can be dated to the calendar year.

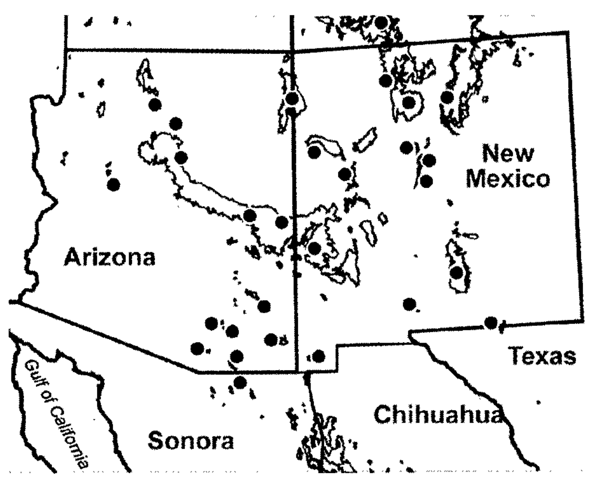

Fig. 9-11. Map of fire history study sites in the southwestern United States. The red dots show locations of tree-ring and fire-scar collections in 27 mountain ranges. Most collections are in ponderosa pine and mixed conifer forests.

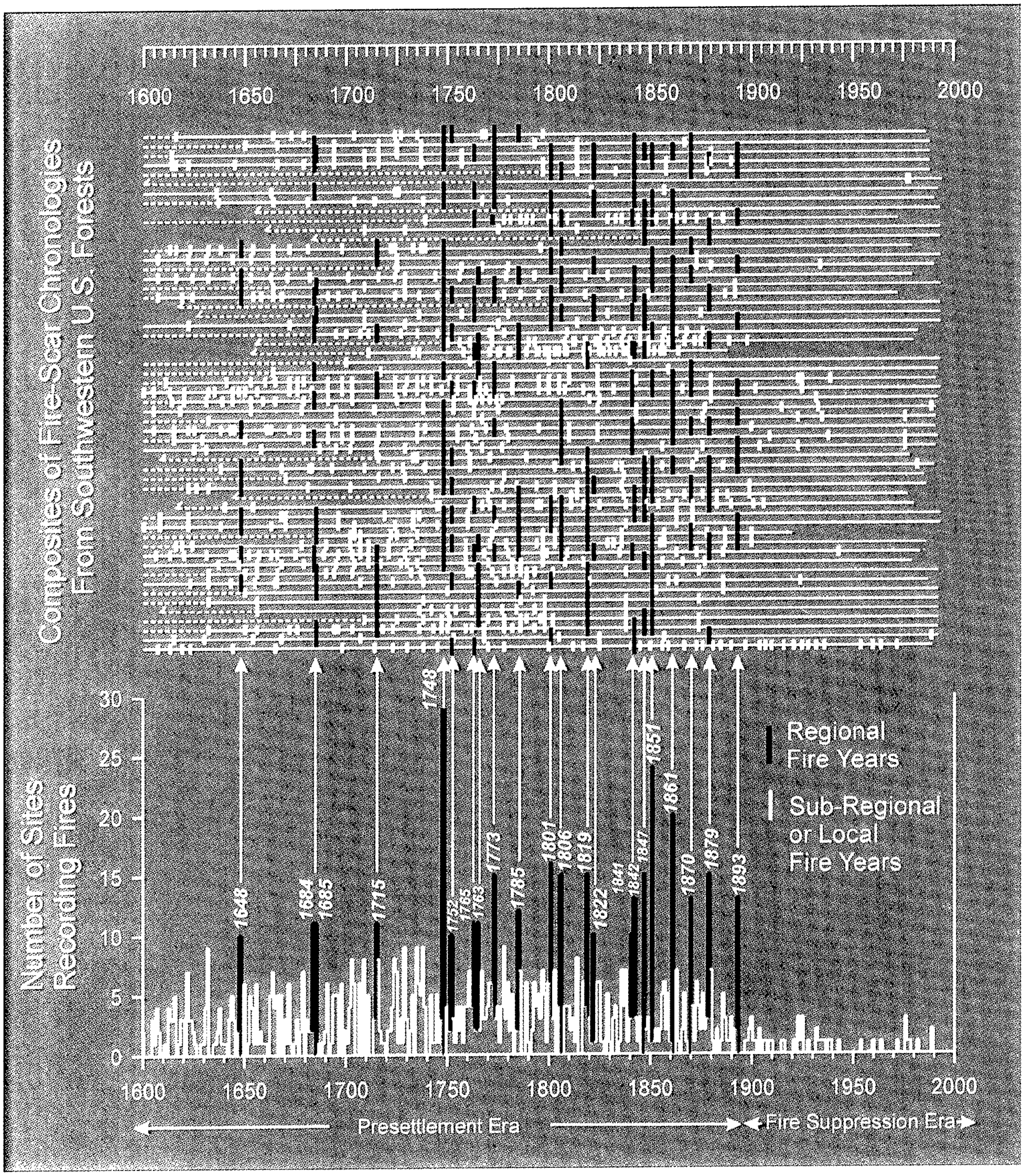

Fig.9-12. Fifty-five fire-scar chronologies for different forest sites in 27 mountain ranges of the southwestern United States. The yellow and red tick marks on each time series are fire dates recorded by fire-scarred trees. At least 10 fire-scarred trees were sampled in each site, and the tree rings and fire scars were dated by dendrochronology methods. Each time series is a composite of the fires recorded by at least two trees in each site. The red tick marks show regional fire years defined by 10 or more of the 55 chronologies (sites) recording the fire date. The yellow tick marks show the other fire dates recorded in nine or fewer sites. The step-line graph at the bottom is a summation of the number of sites recording the fire dates; the regional fire years are in red and are labeled.

of these events demonstrates the importance of interannual climate in controlling local to regional-scale fire occurrence. The El Niño-Southern Oscillation (ENSO), a global climatic pattern, is associated with these fire patterns, both in the past and in current southwestern fire regimes (Swetnam and Betancourt 1990, 1998). Regional fire years tend to occur during La Niña events and droughts, while reduced fire activity corresponds to El Niños and wet years. Moreover, regional fire years tend to occur during average or dry years that follow one to three wet years, indicating the important role of fine fuel production (i.e., grasses and tree needles) in fire dynamics, especially in ponderosa pine forests and lower elevation forests. Hence, when the ENSO has high variation and amplitude, with extreme dry years following extreme wet years, fire activity is entrained across regional scales.

Long-term changes in fire frequency over the past four centuries (Fig. 9-12) were related to both climate and human activities. Native Americans probably set many of the fires recorded by fire scars before 1900, but lightning was (and is) so frequent in the Southwest that, in most places and times, fire frequencies were probably controlled primarily by climate and fuel dynamics, rather than by ignition source. The decrease in fire frequency after the late 1800's (Fig. 9-12) was due mainly to the rise of intensive livestock grazing, when fine fuels (e.g., grasses) that carried surface fires were consumed by millions of sheep, goats, cattle, and horses (Wooton 1908; Swetnam and Baisan 1996). Disruption of fuel continuity by trailing and herding large numbers of animals was probably also involved.

Disentangling climatic factors (regional scale) from cultural factors (local scale) as causes of observed variations can proceed from comparative analyses within a regional network of paleoecological study sites. Interpretations can be based on the degree of synchronism among events across spatial scales and the degree of correspondence among multiple, independently derived time series of disturbance, climate, and land-use chronologies. For example, the importance of intense livestock grazing as a cause of the disruption of natural fire regimes is confirmed by the comparison of different case studies. A few sites in northern New Mexico and Arizona that were grazed by sheep and goats owned by Spanish colonists and Navajos (Diné) show fire frequencies declining in the early nineteenth century, or earlier, and corresponding to the documented timing of pastoral activities in these areas (Savage and Swetnam 1990; Touchan et al. 1996; Baisan and Swetnam 1997). In contrast, remote sites with no evidence of early, intensive grazing sustained some surface fires into the middle of the twentieth century, when aerial firefighting resources began to be most effective in suppressing fires (Grissino-Mayer 1995). Finally, a remote mountain in northern Sonora, Mexico (lowermost fire-scar chronology in Fig. 9-12), where neither intensive livestock grazing nor effective fire suppression has occurred, shows episodic surface fires burning throughout the twentieth century.

One of the strengths of spatial networks of well-dated fire chronologies (or other disturbance chronologies) is that they can be aggregated across spatial scales, providing multiscale spatial and temporal perspectives. Analyzing patterns in such spatio-temporal data networks may reveal scaling rules and underlying mechanisms and controls of disturbance processes (e.g., see Holling 1992). The 1748 fire year in the Southwest (Fig. 9-13) was an example of a cross-scale disturbance event; extensive fires burned at all spatial scales within the region. This extensiveness is indicated by the high synchrony of fires for this date recorded in most sampled trees within stands, in most sampled stands within watersheds, in most watersheds within mountain ranges, and in most mountain ranges within the region. The importance of extreme interannual climate changes in triggering this regional event is indicated by dendroclimatic and Spanish archival sources confirming that 1748 was an extreme drought year following an extremely wet year (1747).

Ecological changes are often best evaluated by comparing multiple lines of historical evidence. Twentieth-century changes in southwestern ponderosa pine forests have been well documented by several generations of ecologists and foresters, ranging from Aldo Leopold (1924) and Gus Pearson (1933) to Weaver (1951) and Covington and Moore (1994). Numerous comparisons of early versus recent photographs and forest stand descriptions have demonstrated that stand densities have increased while grass cover has decreased. These changes were caused by a combination of intensive livestock grazing and, subsequently, organized fire suppression by government agencies. Tree-ring reconstructions of forest age structure and fire history, however, can identify new elements in this story. For example, while many pine forests today are dominated by the post-grazing/fire suppression "tree irruption" of the early 1900's, another pulse of tree recruitment apparently took place during the early 1800's. This pulse is evident in the Monument Canyon Research Natural Area (Fig. 9-14) and other southwestern sites. This pulse corresponds to the longest intervals between widespread fires in numerous sites in the Southwest, changes in fire frequencies and seasonality, and shifts in climate (Grissino-Mayer 1995; Swetnam and Betancourt 1998).

These patterns may indicate that the historical variability in age structures of southwestern ponderosa pine were characterized by pulses of heavy tree recruitment in particularly favorable years embedded in a background of a more continuous but lower level of tree recruitment. Recent studies have confirmed the importance of the famous "1919 seed year" first identified by Pearson (1933) in the Southwest and have demonstrated the role of warm, wet summers in good ponderosa pine seed germination and

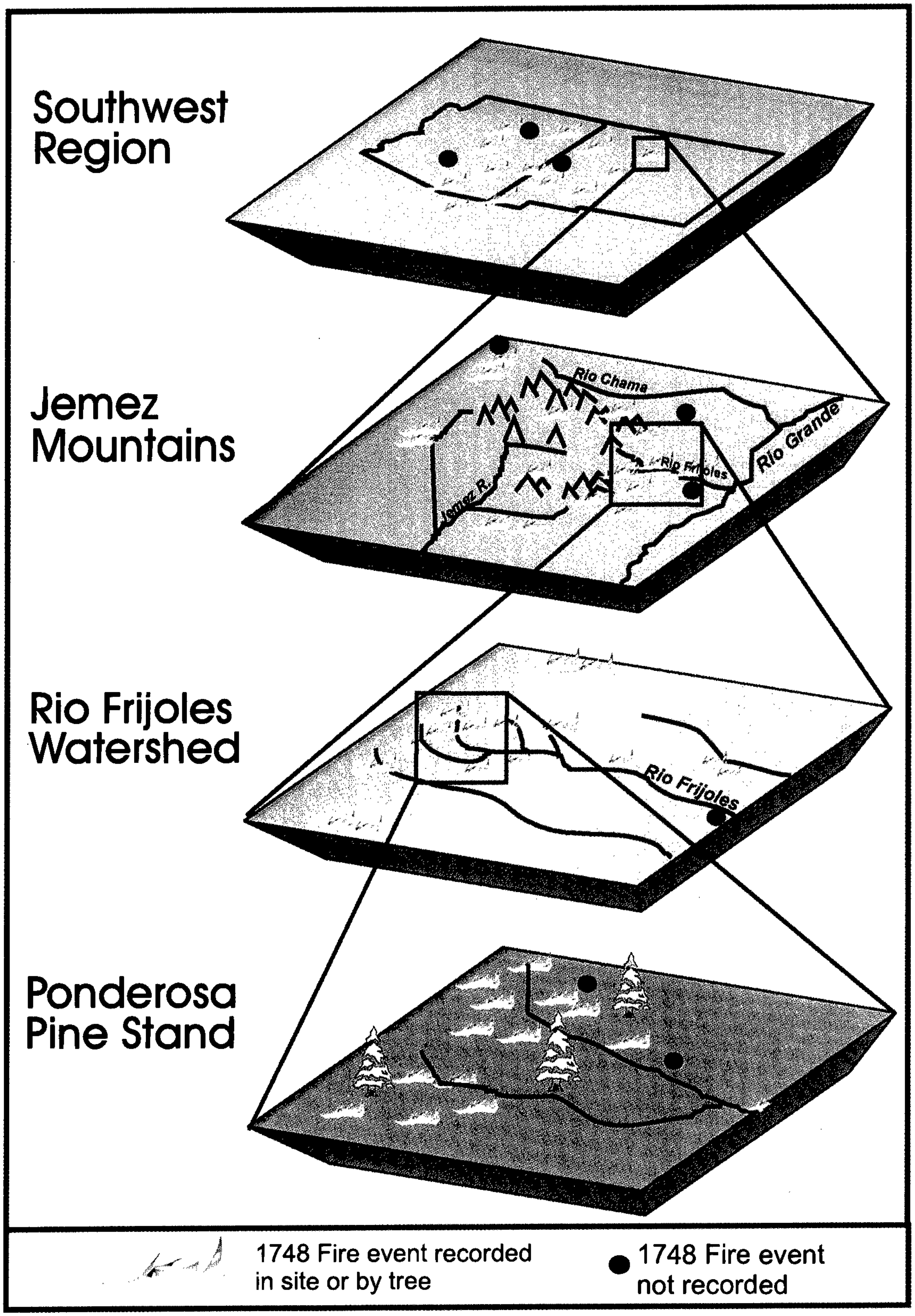

Fig. 9-13. A cross-scale comparison of the largest regional fire year in the Southwest during the past 400 years: 1748. The synchrony of the 1748 fire year among fire-scarred trees at the smallest spatial scale (a forest stand) is shown in the bottom panel. Patterns of synchrony, which are a measure of relative areal extent, are then illustrated at higher levels of aggregation (larger scales, coarser grain size) up through the watershed, mountain range, and finally the regional level (uppermost panel).

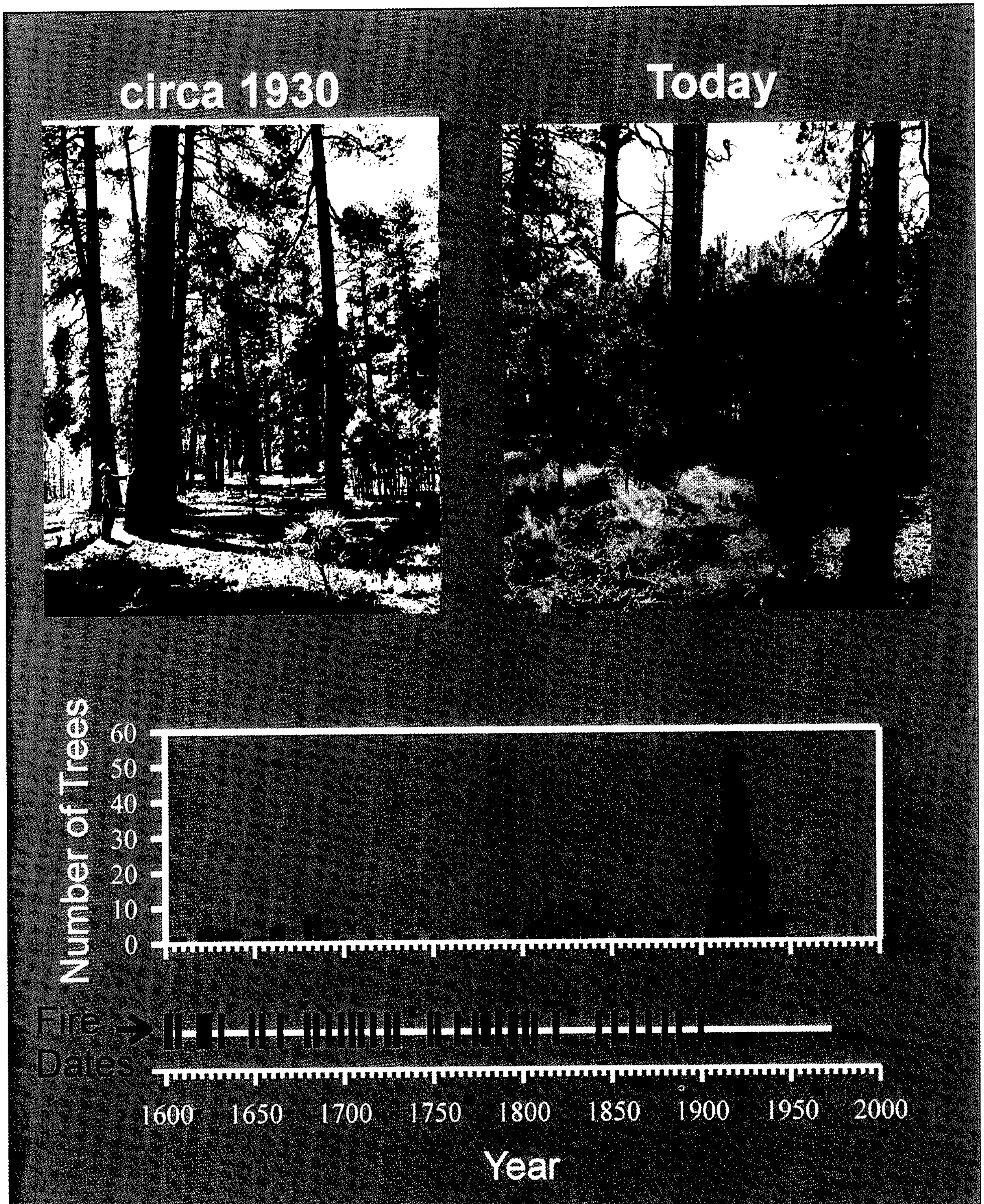

Fig. 9-14. Ponderosa pine forest changes from repeat photography, tree demographic data, and fire history. The upper left photograph is of an open ponderosa pine stand around 1930 with a few clumps of 10- to 20-year-old saplings and the upper right a recent photo of a typical ponderosa pine stand today in Monument Canyon Research Natural Area (RNA), Jemez Mountains. The current stand is choked with dense "dog-hair thickets." The bar graph below the photographs shows the age structure (tree-recruitment dates) of more than 400 trees sampled in the Monument Canyon RNA. The horizontal line with vertical tick marks below the bar graph shows the fire dates recorded by widespread fires within the same stand.

seedling survival (Savage et al. 1996). Hence, ponderosa generational groups were a contingent product of climatic variability and fire regime responses in both the presettlement and postsettlement eras. An implication for new forest restoration initiatives in the Southwest is that current ponderosa forests, characterized by trees that germinated in the 1919 seed year, may not be entirely an artifact of grazing and fire suppression, and therefore thinning programs should not necessarily seek to eliminate this cohort as a distinct demographic pulse.

While climate is often a key driver of plant regeneration in the semiarid Southwest, ultimately it is the linked influences of climate, fire regimes (and other disturbances), and land-use histories that determine the demography of plant populations and southwestern vegetation patterns. These interactive effects are demonstrated by the extensive mortality of ponderosa pines and pinyon during the 1950's drought in the Southwest (Betancourt et al. 1993; Allen and Breshears 1998), as the drought effects (climate) were likely exacerbated by competition for scarce water among unusually dense stands of woody plants (a result of modern changes in land use and fire regimes). Also, while a pulse of tree seedlings has established since about 1976 in southwestern forests and woodlands (Swetnam and Betancourt 1998) in conjunction with a recent wet period (associated with an unusual string of El Niño events), the survivorship and ultimate recruitment of these trees partly depends upon patterns of land use and fire. Monitoring of these current demographic processes and reconstruction of past patterns are needed to fully understand ongoing changes and their historical context.

Summary

Several important themes emerge from the illustrations of southwestern environmental change discussed here.

1. High-resolution, long-term, (and in some cases unique) historical and paleoecological data sets, coupled with diverse, specialized approaches for reconstructing landscape change, are available to detect and explain trends in ecological patterns and processes across southwestern landscapes.
2. Network approaches are very useful in the development of regional historical data sets which can be utilized to construct land use histories. By aggregating data spatially, observations and inferences can be scaled up from localities to landscapes and entire regions. Development of regional time-series networks provides opportunities to quantify both spatial and temporal variability as a function of scale.
3. Climatic variability is a key driver of ecological processes; it also modulates human land uses and their effects on southwestern landscapes. Regional climatic signals must be extracted before landscape changes can be attributed to other causes, such as human activities.
4. All landscapes are historically contingent systems whose structure and dynamics reflect continuous modification of preexisting systems (Brown 1995). Historical data can be used to discriminate between natural and cultural causes of environmental change. Environmental variability and trends have regional and local components. One effective approach to determining causation is to identify synchronous regional responses of biotic systems (which are often climate-driven) and asynchronous, disparate responses observed at local scales (which are often attributable to human land uses and other local disturbances). Additionally, comparison of multiple lines of evidence from different types of ecological reconstructions (e.g., photographs, tree ages, fire scars, cultural histories, climate records) can be the key to identifying causal factors.
5. Historical data can be used to define and constrain natural ranges of variability, providing important information for management of ecosystems and landscapes (Allen 1994). In the case of wilderness areas and parks, these perspectives may be directly relevant to setting management goals or targets. In other cases, improved knowledge of the origin of existing ecosystem conditions will be the primary value of historical data. Ecosystem management efforts to sustain valued wildland resources (from endangered species to surface water) will benefit from improved knowledge of the patterns and causes of past environmental change.

Much unrealized potential exists to develop detailed land use histories and associated causal narratives in the Southwest. Valuable initiatives would include further regionalization of localized paleoecological data sets (e.g., tree-ring collections), systematic programs to assemble and use repeat photographs (including the extensive aerial photography of the mid-1930's), regional-scale applications of the extraordinary wealth of archeological data present in the Southwest to environmental histories, and the development of regional approaches to monitoring ongoing changes in landscape patterns.

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Chapter 10: Biodiversity and Land-use History of the Palouse Bioregion: Pre-European to Present

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Abstract. We present a regional land-use history of the Palouse bioregion of southeastern Washington and west-central Idaho. Our objectives were to develop a history of European-American settlement and biological diversity in the region and use this history to understand how human activities have altered the land cover and ecological integrity of the Palouse bioregion. We compiled and interpreted available information on people, plants, animals, and physical resources over time. We found a multiscale approach imperative due to different spatial scales of key features, different data structures for social and ecological information, and different time scales and geographic coverage. Since 1870, 94% of the grasslands and 97% of the wetlands in the Palouse biogregion have been converted to crops, hay, or pasture. For a small (875-ha) but representative area examined in more detail, less than 1% that once supported grasslands or wetlands do so today. Most of the remaining small patches of grassland and riparian vegetation disappeared between 1940 and 1989. Today, some once common fauna and endemic flora survive only in small areas of grassland, shrub, and forest, and these remnants are threatened by weed invasion, herbicide drift, and introduced species. Social and ecological changes were episodic and related to eras of agricultural technology: European-American settlement (1870-1900), horse-powered agriculture (1901-30), industrial agriculture (1931-70), and suburbanization (1971-90). Understanding the biophysical changes that have occurred in this region provides a useful starting point for outlining future research needs, establishing conservation goals, and targeting ecological restoration efforts.

Introduction

If men could learn from history, what lessons it might teach us! —Samuel Taylor Coleridge 1836

What is the value of history to ecology? More specifically, what can historical, time-series data tell us that is relevant to current land management? We addressed this question by looking at how humans have influenced the Palouse Prairie of west-central Idaho. Our objectives were to (1) develop a history of European-American settlement and biological diversity in the Palouse bioregion, (2) use this history to understand how human activities have altered land cover and ecological integrity of the bioregion, and (3) assess the utility of information of differing scales and time periods. We believe that understanding the biophysical changes that have occurred in this region will provide a useful starting point for establishing research hypotheses, conservation goals, and ecological restoration efforts.

Land use is a function of culture and settlement pattern as well as environmental characteristics (Meinig 1968; Rappaport 1968; Bennett 1976; Robbins et al. 1983). The interactions of social, economic, and ecological factors are described in a large, diverse literature. Measures of social and economic conditions that have been shown to influence or be correlated to land-use patterns include historical land use (Turner and Meyer 1991; Savisky 1993; Flamm and Turner 1994), rural population density (Clawson 1971; Jobes 1991; McKendry and Machlis 1993), economic land value (Odum 1936; Alig 1986), tax status (Odum 1936; Fortmann and Huntsinger 1989; Savisky 1993), access (Turner et al. 1991; Skole et al. 1994), type of owner (Tosta and Green 1988; Fortmann and Huntsinger 1989; Turner and Meyer 1991; Savisky 1993; Skole et al. 1994), and residency of owner (Fortmann and Huntsinger 1989; Rudzitis and Johansen 1989; Fortmann and Kusel 1990; Jobes 1991).

Measures of ecological conditions demonstrated to influence or interact with land use include land cover and successional stage (Odum 1936; Rudel 1984; Forman and Godron 1986; Johnson 1987; Tosta and Green 1988; Boyle 1991; Dale et al. 1993; Flamm and Turner 1994; Koopowitz et al. 1994), soil type (Johnson 1987; Iverson 1988; Aspinall et al. 1993; Dale et al. 1993; Savisky 1993; Flamm and Turner 1994), physiography (Johnson 1987; Iverson 1988; Tosta and Green 1988; Ludeke et al. 1990; Savisky 1993; Schreier et al. 1994; Flamm and Turner 1994; Riebsame et al. 1994), climate (Hendrix et al. 1988; Ludeke et al. 1990; Riebsame et al. 1994), and biodiversity (Boyle 1991; Dale et al. 1993; Flamm and Turner 1994; Koopowitz et al. 1994).

Methods

Study area

The Palouse bioregion (Bailey 1995) covers 16,000 km^2 in west central Idaho, southeastern Washington, and northeastern Oregon between the western edge of the Rocky Mountains and the Columbia River basin (Fig. 10-1). The region is characterized by a moderate climate and loess soils deposited on plateaus dissected by rivers deeply incised through layers of bedded basalt.

The climate is unusually temperate for an area so far inland. Hot, dry summers follow relatively warm, wet winters and long, cool, damp springs. Most precipitation falls as rain, though snow and rain-on-snow events are not uncommon. The highly productive loess dunes which characterize the region are Pleistocene in origin (Alt and Hyndman 1989). Having been deposited by southwest winds, the steepest slopes (up to 50% slope) face the northeast. The dune-like topography and northeastern orientation are important ecological features; the lee slopes are moist and cool, and level areas tend to be in the bottom lands. Due to their ontogeny, low-lying areas are often disconnected from stream systems and are thus seasonally saturated.

The Palouse Prairie, on which we focus, lies at the eastern edge of the Palouse bioregion, north of the Clearwater River. Here, where the loess hills are most developed, soils are often more than 100 cm deep. The depth and fertility of the soils make the region one of the world's most productive grain-growing areas (Williams 1991).

Approach

It is well known that the Palouse bioregion has undergone extensive change over the past 125 years. Both biophysical and human changes have been closely associated with advances in agricultural technology. Therefore, we structured our analysis using four time periods that

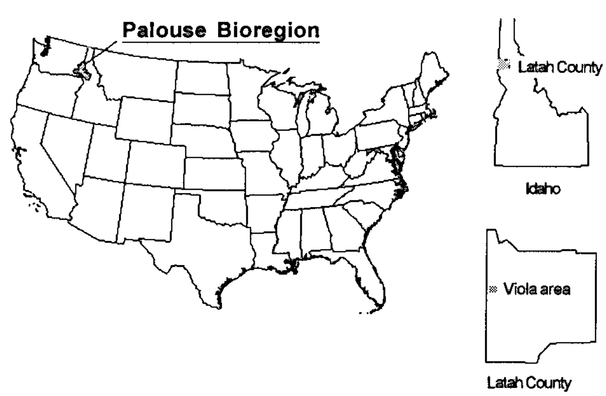


Fig. 10-1. The Palouse bioregion, modified from Bailey (1995), and three spatial scales of the analysis: bioregion, county, and a small (875 ha) focal area.

bracket major changes in technology: European-American settlement (1870-1900), horse-powered agriculture (1901-1930), industrial agriculture (1931-1970), and suburbanization (1971-1990).

Because we knew both social and ecological changes in the bioregion would occur over and be detectable at different spatial scales, we conducted our analyses at three different levels: bioregion, county, and an 875-ha focal near Viola, Idaho (Fig. 10-1). This multiscale approach also allowed us to take advantage of data collected and reported at different spatial scales and geographic extents. In general, data available for the entire basin were coarser than those obtained for the county; data for the small area were at a yet finer spatial resolution.

Data for the broad scale encompassed the entire Palouse bioregion. We used both historical and current vegetation, mapped at a 1-km^2 spatial resolution, from the Interior Columbia River Basin Ecosystem Management Project (Quigley and Arbelbide 1997). The historical vegetation data were derived from a combination of expert opinion, modeling, and historical records. The current vegetation was classified from satellite imagery. Historical and current fire regimes, which describe the frequency and severity of typical fires, were modeled by expert opinion from these layers (Morgan et al. 1996, Quigley and Arbelbide 1997).

At the county scale, we used soil surveys and published literature to predict reoccurrence of historical distribution (Kincaid and Harris 1934; Daubenmire 1942; Tisdale 1961; U.S. Department of Agriculture 1978; Ratti and Scott 1991). The U.S. Department of Commerce (1890, 1900, 1930, 1950, 1959, 1970, 1974, 1990, 1992) provided data on human settlement and social patterns (economic, demographic, and land use changes); these data have been recorded at the county level since the mid-1800's. Where data were available for all counties in the bioregion, we report bioregion-wide information. Where data were less accessible or unavailable for all counties, we concentrated on three counties that typify the region (Lewis and Latah Counties in Idaho and Whitman County in Washington).

Bioregional and county-level measures are often too coarse for tracing change in local biological resources because ecological boundaries are often smaller than those of the county or they do not coincide with political boundaries. To more accurately track land use and landcover changes at a finer scale, we examined an 875-ha area near Viola, in Latah County, Idaho, that contained the four major Palouse Prairie vegetation types (grass, shrub, dry forest, and riparian). This area was selected because historical aerial photographs were available from the Latah County courthouse and the area is typical of the bioregion. Vegetation and land use were interpreted from the aerial photographs (1940, 1965, and 1989, approximately 1:16,000). Vegetation and land-use boundaries were interpreted on mylar overlays, then digitized, georeferenced, and entered into a geographic information system (GIS) database. Information on tax status, market value, parcel size, and type and residency of owners for each parcel of land was obtained from county courthouse records.

To describe past-to-current change in vegetation at the fine scale for a longer but unknown time interval, we used a digital map of soils and potential vegetation for Latah County (Barker 1981) to project past vegetation based upon soil characteristics. Where soils were hydric, as indicated by the color of reduced iron compounds when described in the original field survey, the past vegetation was mapped as wetlands. Soils described as including hydric soils were mapped as potential wetlands to reflect the high probability that the area included small areas of wetlands. Soils that now support forests or had characteristics suggesting development under mostly forested conditions, such as low organic matter and light color, were mapped as forest. All others soils were mapped as grasslands. In addition, we generated and overlaid a map of areas that have a perched water table within 1.5 m of the surface to highlight areas that would have significantly more water available.

Our analyses and interpretations were primarily graphical. We used a GIS extensively to assemble and compare mapped information. For instance, we calculated the differences in extent of historical and current vegetation at the broad scale. Our synthesis of information on human demographics, land use, land cover, and biophysical resources since the turn of the twentieth century was necessarily descriptive. Because information was not available for or reported at consistent spatial and temporal scales, opportunities for quantitative comparisons across either time or space were limited. To strengthen and support our analysis, we relied on multiple lines of evidence at multiple spatial scales.

Results and Discussion

The Palouse Bioregion Prior to European-American Settlement

The vegetation encountered and documented by the earliest European-Americans cannot be considered to represent "stable" conditions, conditions that had been consistent for several generations of inhabitants and processes. The first inhabitants of the Palouse region, ancestors of the present-day Nez Perce Indians, probably arrived more than 12,000 years ago. For at least the last 2,000 years of that time, they lived in the river canyons, harvesting salmon during spring, summer, and fall and traveling to the prairies to harvest camas bulbs (mostly *Camassia quamash*) in the spring (Josephy 1965; Meinig 1968). Their economy was based on locally harvested wildlife, including salmon (*Oncorhynchus* spp.), elk (*Cervus elaphus*), and mule deer (*Odocoileus hemianus*), and was supplemented by traded goods from both the west coast and interior areas (Josephy 1965; Chalfant and Ray 1974).

In the 1700's, two major events affected the Nez Perce Indians: domesticated horses were introduced, and the Indian population was decimated by smallpox. The Nez Perce people numbered between 4,000 and 8,000 in the Northwest until major smallpox epidemics began in the 1780's. By the mid-1830's, their population had crashed to about 2,500 (Meinig 1968; Boyd 1985; Fig. 10-2). We cannot fully know how these changes affected the vegetation that existed in the late 1800's. However, Indian use of fire and harvesting of camas bulbs undoubtedly declined relative to previous centuries.

Based on early settlers' descriptions of vegetation and wildlife habitats (e.g., Buechner 1953; Kaiser 1961; Meinig 1968) and more recent botanical assessments of prairie remnants (e.g., Weaver 1917; Daubenmire 1942; Tisdale 1961), we know that prior to settlement by European-Americans, bunchgrasses dominated the Palouse bioregion. Most of the original perennial grass prairie, though, was gone by 1900. One of the hindrances to fully understanding the ecological changes that have occurred on the Palouse Prairie is the lack of early natural history studies in the area. Weaver (1917) noted, "In the great inland province, practically no botanical work except of a taxonomic character has been done."

Prior to 1900, the native grasslands occurred in three zones (Daubenmire 1942; Tisdale 1961). The more mesic zone, on the wetter, eastern edge of the Palouse Prairie, was dominated by two perennial grass species, Idaho fescue (*Festuca idahoensis*) and bluebunch wheatgrass (*Psuedoregneria spicata*). Climax shrub communities, particularly bluebunch wheatgrass-snowberry (*Symphoricarpos* spp.) but also black hawthorn (*Crataegus douglasii*) and rose (*Rosa* spp.), grew on the northern sides of many of the loess hills (Lichthardt and Moseley 1996). Throughout this zone, summer moisture was too low to sustain trees except near streams (Lichthardt and Moseley 1996). The western portion of the Palouse Prairie was drier, though also dominated by bluebunch wheatgrass (Tisdale 1961). A third distinctive community occurred in the Snake River and Clearwater River canyons. These areas were far hotter and drier than the prairies and supported a sparser bunchgrass/shrub community (Tisdale 1986). Draws and waterseeps in the canyons supported a rich variety of tree species, including hawthorn and mock orange (*Philadelphus lewisii*).

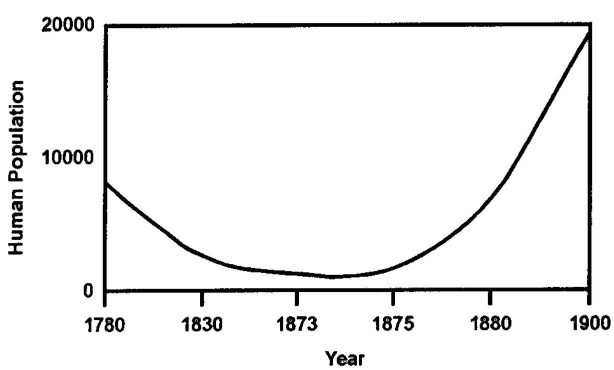


Fig. 10-2. Human population change on the Palouse Prairie. European-Americans began settling the area about 1874 (Josephy 1965; U.S. Dept. of Commerce 1890, 1900).

True riparian communities were largely limited to the Palouse and Potlatch Rivers and to the broad outwash plains along sections of the Snake and Clearwater Rivers. These riparian zones supported a narrow gallery forest of plains cottonwood (*Populus deltoides*), quaking aspen (*P. tremuloides*), mountain maple (*Acer glabrum*), and red alder (*Alnus rubra*; Daubenmire 1942; Tisdale 1986). Wetlands were important but scattered. The vegetation was diverse and typically dominated by camas, a mixture of forbs, and many grasses.

Forest communities occupied the higher elevation mountains and ridges. On warmer sites, ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*) grew with a rich shrub understory dominated by oceanspray (*Holodiscus discolor*), ninebark (*Physocarpus malvaceus*), serviceberry (*Amelanchier alnifolia*), snowberry, and wild rose. Cooler north- and west-facing canyons supported some western redcedar (*Thuja plicata*), grand fir (*Abies grandis*), and western larch (*Larix occidentalis*; Daubenmire 1942; Tisdale 1986).

Changes in Settlement and Economy

European-American Settlement (1870-1900)

European-American settlement began with prospectors in the 1860's when precious metals were discovered in streams just east of the forest/prairie margin. By the end of the 1860's, settlers had claimed creek bottom lands around Paradise Valley (near present-day Moscow, Idaho), Union Flat Creek, and the upper Palouse River. The Palouse was politically organized during the 1870's and 1880's. By 1890, half the land in Whitman County was being farmed (Fig. 10-3), and by 1900, the population was just under 20,000 (Williams 1991; Fig. 10-4). Weaver (1917, p. 3) stated, "Only isolated tracts of the best developed prairies remain intact, while hundreds of acres of the drier bunchgrass lands have been broken up during the times [1912-14] of the progress of this work."

The European-American settlement and land-use patterns differed dramatically from Native American practices. Native Americans lived in the river valleys, while European-Americans lived on the prairies. Native Americans were hunter-gatherers or low-impact agriculturists of native species; the European-Americans were high-impact agriculturists of introduced species.

Initially, European-Americans used the Palouse hills as pasture, but farmers soon discovered the soil's fertility

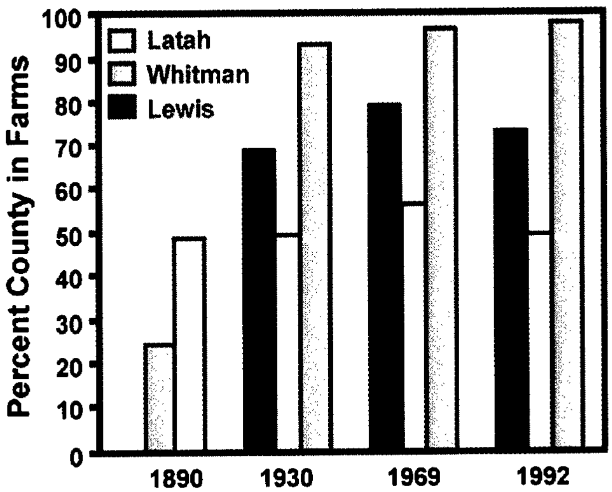


Fig. 10-3. Percent of total land area in farms through time in Latah, Lewis, and Whitman Counties (U.S. Department of Commerce 1890, 1930, 1970, 1992).

(Prevost 1985). Fruit was an important early, though short-lived, commercial crop in the Snake River canyon and other areas in the Palouse. Apples, peaches, prunes, plums, apricots, and pears thrived (Williams 1991). However, both competition from areas better suited for fruit production and a better return on investment for wheat farming effectively killed the local fruit industry (Williams 1991).

Grain farming initially began on drier meadows and lower side slopes, leaving the steep hills, hilltops, and wet meadows for livestock pasture. Within as few as 10 years after first plowing, however, water tables in low-lying meadows dropped sufficiently to allow tilling (Victor 1935).

Lack of efficient transportation systems posed marketing problems for early farmers. Though steamboats operated up to the junction of the Snake and Clearwater Rivers, the rivers were low during the critical summer months, and the roads to the river ports were deep with dust in the summer and mud during the long spring and fall. Moving grain 30 miles from farms to ports on the Snake River often took 2 days if the wagons mired in the mud or dust (Williams 1991). Grain farming was also labor intensive, relying on human- and horse-power. Though steam-driven threshers appeared on the Palouse Prairie in the late 1800's, each

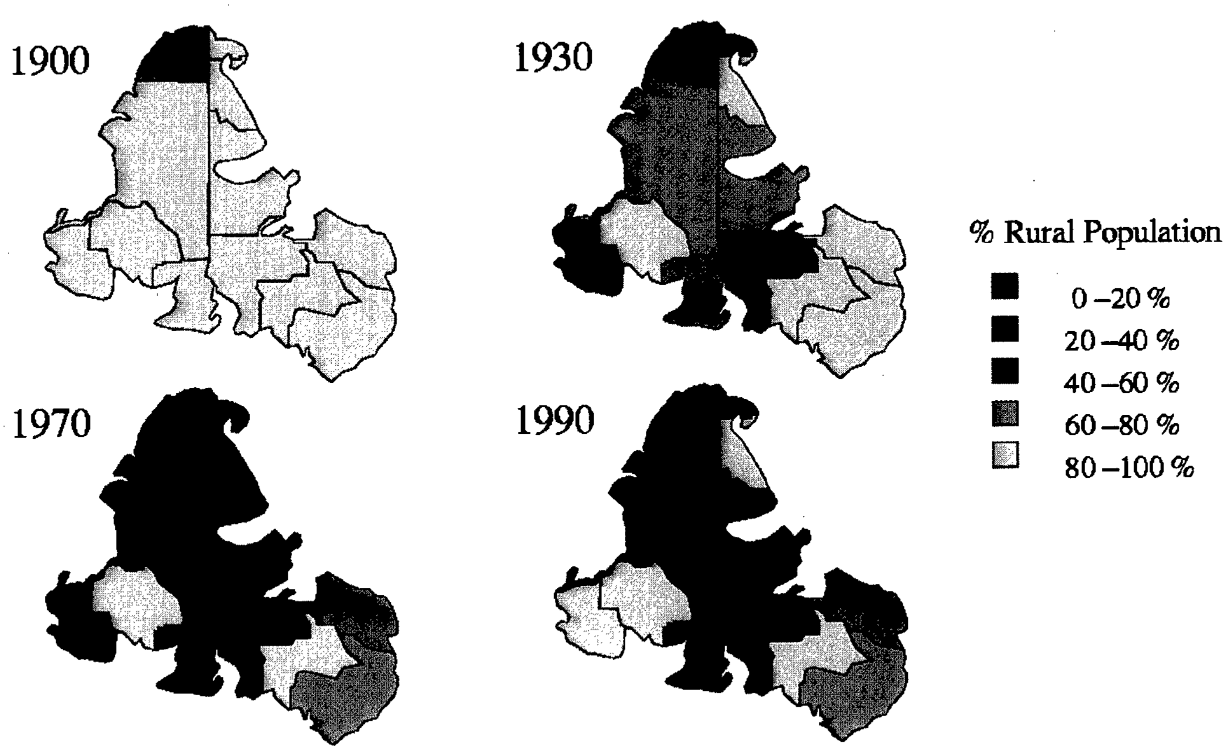


Fig. 10-4. Changing proportion of the human population living in rural areas (U.S. Department of Commerce 1900, 1930, 1970, 1990).

machine required 18 horses and many men to operate (Prevost 1985). Many horses and cattle were used as draft animals on the farms, and all of these animals needed year-round pasture.

The combination of relatively inaccessible markets, considerable untillable lands, large pasturage requirements, and high labor requirements created a landscape that contained considerable refugia for native flora and fauna.

Horse-powered Agriculture (1901-30)

Major changes in land use between 1901 and 1930 resulted from the intensification of agriculture. Development of an extensive railroad network just after the turn of the century opened markets outside of the Palouse area. Farming became commercialized. Wheat and other cereals well adapted to the hillsides and climate of the Palouse region (Williams 1991) emerged as the dominant crops. The human population continued to grow (Fig. 10-4); by 1910, there were 22,000 people in 30 communities across the Palouse Prairie.

Farming remained labor-intensive and still relied heavily on human- and horse-power. An organized harvesting/threshing team in the 1920's required 120 men and 320 mules and horses (Williams 1991). The quest for a less labor-intensive bushel of wheat continued, but combine use lagged behind other farming areas in the United States (Williams 1991). It was only when the Idaho Harvester Company in Moscow began to manufacture a smaller machine that widespread combine harvesting became feasible. By 1930, 90% of all Palouse wheat was harvested using combines (Williams 1991). Such improvements enabled farmers to use lands previously left for grazing and as "waste," but the steepest hills and hilltops were still left as pasture for cattle and horses.

Industrial Agriculture (1931-70)

The era between 1931 and 1970 was one of continued mechanization, and especially industrialization. With the development of each new technology, farming became less labor intensive, allowing fewer people to farm larger areas (Fig. 10-5). Petroleum-based technology replaced horse and most human labor early in the era. By 1970, most farm workers used motorized equipment, which removed the need for pasture lands and provided equipment that could till even the steepest slopes. Fertilizers, introduced after World War II, increased crop production by 200%-400%. Federal agricultural programs encouraged farmers to drain seasonally wet areas, allowing farming in flood plains and seasonally saturated soils. With the advent of industrial agriculture, the last significant refugia for native communities were plowed.

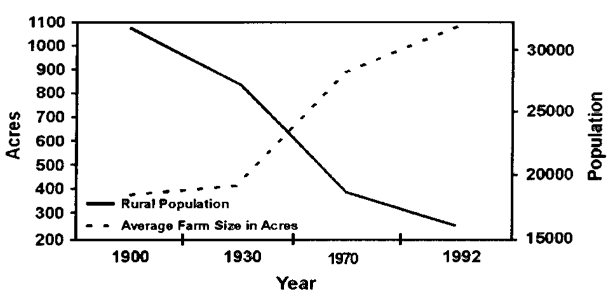


Fig. 10-5. Rural population and average farm size through time for Whitman County, Washington (U.S. Department of Commerce 1900, 1930, 1970, 1992).

Suburbanization (1971-90)

Since 1970 major changes have occurred in the composition of the rural population and land use. Rural population began to rise as more town and city residents sought rural suburban homesites. Ironically, yesterday's farmers and their children who still own farm land have moved to ever more distant towns and cities (unpublished data from Latah County records). The influx outweighs the exodus, however, and human populations in rural areas are growing. Little change has occurred in overall hectares devoted to agriculture; however, some lands with highly erodable soils have been temporarily removed from crop production under the Federal Conservation Reserve Program (CRP). In Latah County alone, this program removed about 14,000 ha from agricultural production (U.S. Department of Agriculture 1996a), most planted with introduced perennial grasses. Because the Palouse Prairie has been declared an endangered ecosystem (Noss et al. 1995), current CRP guidelines encourage restoration of endangered native ecosystems (U.S. Department of Agriculture 1996b). Within Latah County, an additional 1,559 ha have been included in the Idaho Fish and Game Department's Habitat Improvement Program. Ponds and plantings on the latter lands are designed to enhance nesting habitat for upland game birds.

Ecological Change

The effects of prairie conversion can be seen in both social organization and ecosystem composition. Instead of living in the river canyons and foraging on the prairies, people now live on the prairies, cultivate the former wild meadows, and recreate in the river canyons. Local economies are based on extraction rather than subsistence. With each advance in agricultural technology, crop production has increased and more native prairie vegetation has been converted to field or pasture. First the draining of wetlands, then equipment that enabled farming of steep slopes, then the introduction of chemicals; each effectively shrank remaining refugia for native flora and fauna. Grazing and farming introduced new species and imposed a different set of disturbance regimes on the landscape.

Suburbanization of the rural landscape represents the second major land-use conversion in the last century. As with the first, this change will have a profound influence on ecological processes and biological diversity.

Change in Vegetation

We used broad-scale information to monitor changes in grass, shrubs, and forest vegetation across the bioregion. Since 1900, 94% percent of the grasslands and 97% of the wetlands in the Palouse bioregion have been converted to crop, hay, or pasture lands (Fig. 10-6). Approximately 63% of the lands in forest cover in 1900 were forested in 1990, 9% were grasslands, and 7% were regenerating forest or shrub vegetation. The remaining 21% of previously forested lands have been converted to agriculture or urban areas.

These broad-scale comparisons did not allow us to distinguish subtle differences in vegetation type such as in forest structure or species composition. Most of the forested lands in the region have been logged one or more times. Removal of the more marketable tree species and sizes alters forest structure and wildlife use. At 1 km^2, the broad-scale analysis also lacks the spatial resolution

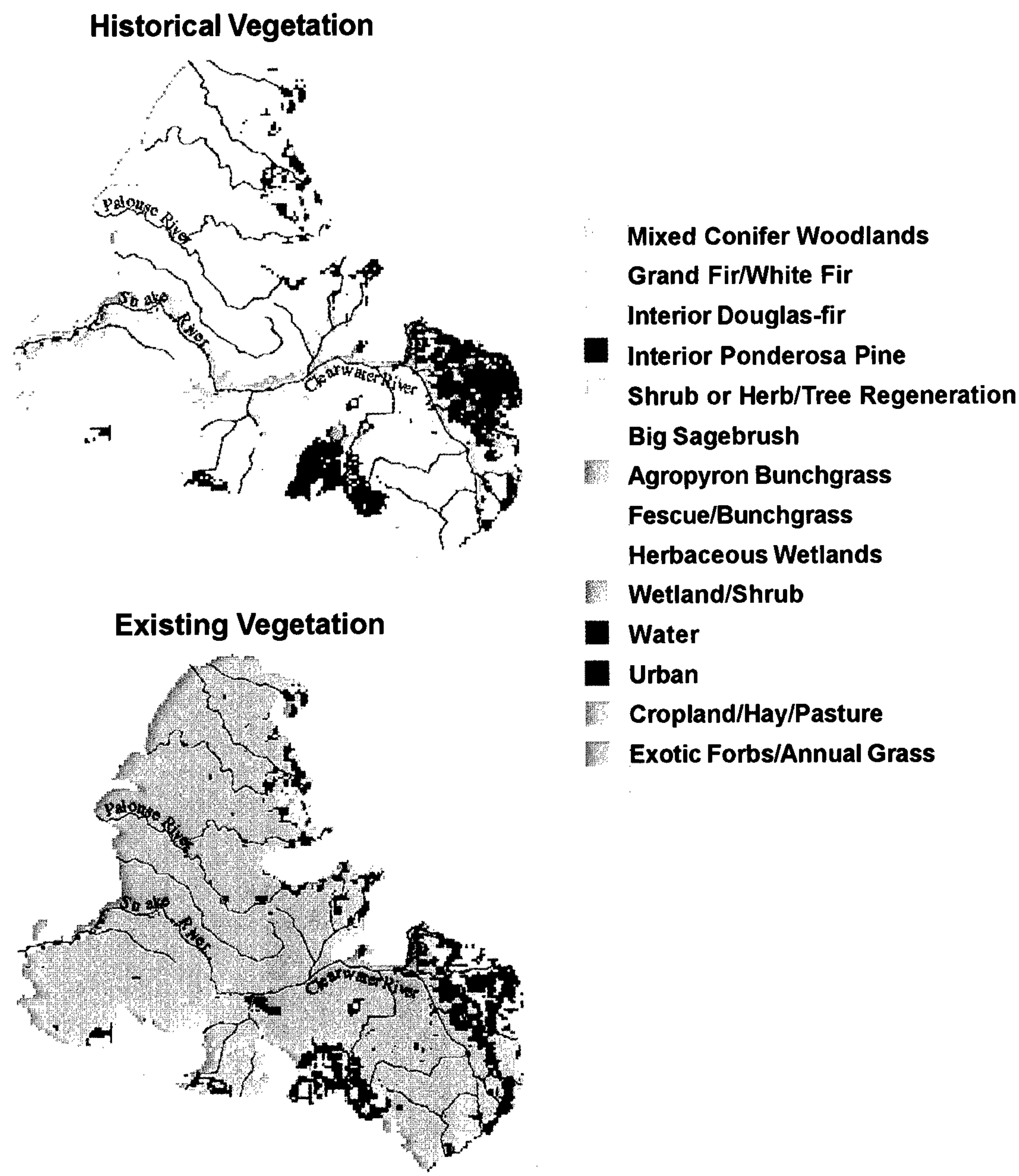


Fig. 10-6. Historical (circa 1900) and current (circa 1990) vegetation in the Palouse bioregion (Quigley and Arbelbide 1997).

necessary to detect changes in the number and composition of small patches, connectivity, and other fine-grained landscape patterns.

We believe that these results vastly underestimate the past abundance of riparian areas and the small patches of wetlands and shrubs once common on the Palouse Prairie. The fine-scale topography of the Palouse hills would have harbored many wetlands of a size too small to be captured at a 1-km^2 scale. In addition, such changes were captured only over the last 90 years, 40 years after European-Americans began to settle in the area.

To identify probable locations and extents of habitats under-represented at the broad scale, we conducted two finer-scale analyses. We found ecologically significant changes in small patches of brush, grass, and riparian vegetation from 1940 to 1965 and 1965 to 1989 in the 875-ha area evaluated with historical aerial photographs (Fig. 10-7). A total of 170 ha (19.4% of the total area) was converted to agriculture between 1940 and 1965, mostly from open shrublands and riparian areas. Most forest lands were logged during this period, creating open forests with shrubs. Although significant conversions of riparian areas to fields and pastures probably occurred between 1880 and 1940, 61% of riparian areas existing in 1940 were gone by 1989. Stringers of riparian vegetation shrunk to thin, broken tendrils, and shrub vegetation virtually disappeared. If this 875-ha area is indeed representative of the entire bioregion, the cumulative effects of such changes are enormous. Alteration in the size, quality, and connectivity of habitats may have important consequences for wildlife species (Forman and Godron 1986; Soule 1986).

We also predicted past vegetation extent based on soil characteristics. This process was particularly useful for mapping areas where wetlands existed long enough to result in hydric characteristics. It revealed much more extensive riparian or wet areas than shown over the last century at the broad scale or over the last 50 years at the fine scale (Fig. 10-8). One plausible reason for this difference is that extensive changes undoubtedly occurred prior to either 1900 (the date of our earliest broad-scale vegetation map)

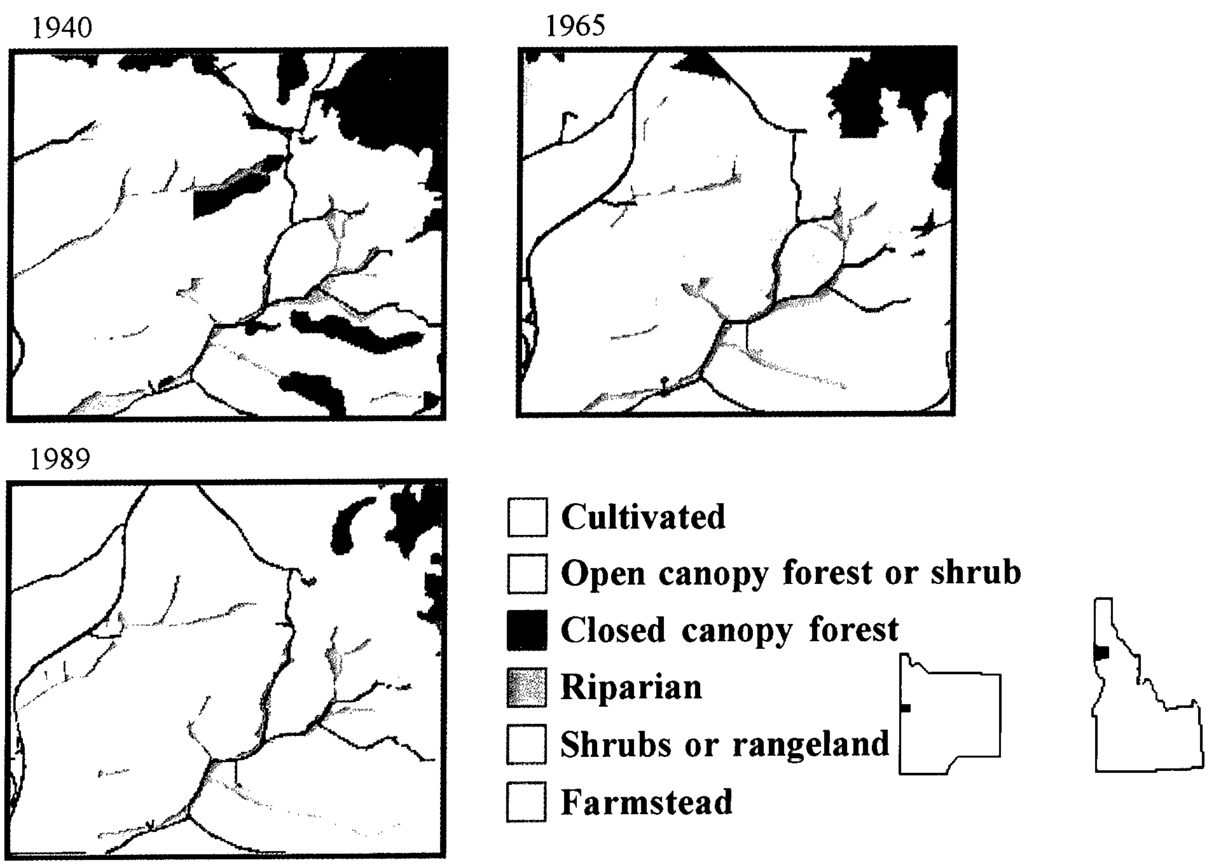


Fig. 10-7. Changing vegetation over time as interpreted from aerial photographs of a small (875 ha) area near Viola, Idaho.

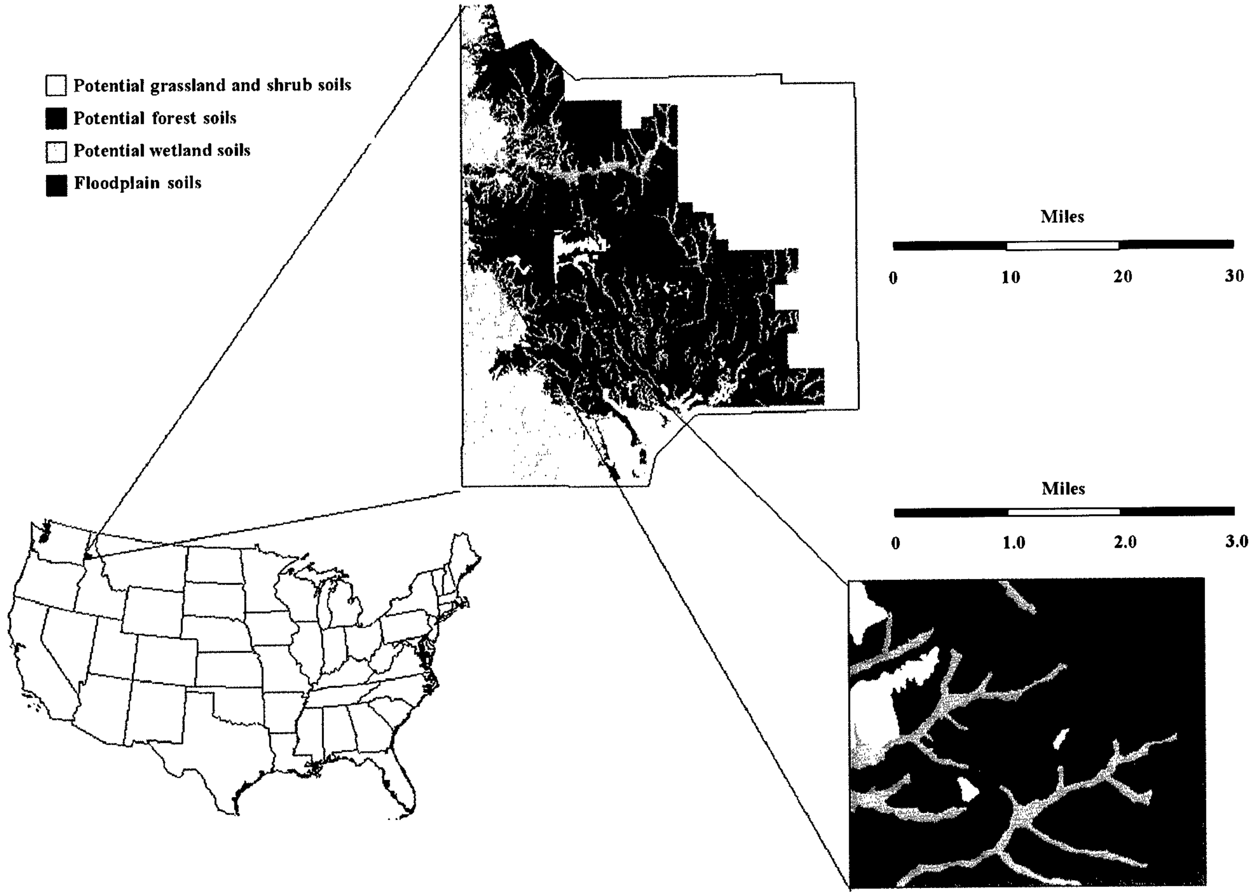


Fig. 10-8. Past vegetation predicted from soil characteristics for Latah County, Idaho, and the 875-ha area near Viola, Idaho.

or 1940 (the date of our earliest aerial photograph). Another plausible explanation is that the soil characteristics are a legacy of past climate, such as the Little Ice Age that ended in the early 1800's (Pielou 1991). The soils may have developed during a preceding cooler, wetter period when forest cover was more extensive than at present. Under the slightly warmer and drier present-day climate regime, one would expect a retreat of the forest margins. We hypothesize that the forest extent before European settlement was greater than today, but not as extensive as our "potential vegetation" map suggests, and that wetlands were more extensive in the past than they are today.

Change in Biodiversity

Of the once-continuous native prairie dominated by midlength perennial grasses, only little more than 1% remains. It is one of the most endangered ecosystems in the United States (Noss et al. 1995), and all remaining parcels of native prairie are subject to weed invasions and occasional drifts of aerially applied agricultural chemicals (J. Lichthardt, personal communication). Two of the native plant communities, bluebunch wheatgrass-snowberry and bluebunch wheatgrass-rose, are globally rare, and eight local plant species are threatened globally (Lichthardt and Moseley 1996). Many once-intermittent streams are now farmed; many perennial streams with large wet meadows adjacent to them are now intermittent or deeply incised, and the adjacent meadows are seeded to annual crops. Few areas of camas bloom in the spring. Clean farming practices (field burning, herbicide use, and roadbed-to-roadbed farming) leave few fences and fewer fencerows, negatively impacting even those edge species which can flourish in agricultural areas (Ratti and Scott 1991).

With the virtual elimination of native prairies, species dependent on grassland ecosystems have declined or disappeared as well. Formerly abundant sharp-tailed grouse (*Tympanchus phasianellus*) occur only in highly fragmented, marginal, and disjunct populations (Kaiser 1961; Burleigh 1972; U.S. Department of Agriculure 1978; Ratti and Scott 1991). The white-tailed jack rabbit (*Lepus townsendii*) and ferruginous hawk (*Buteo regalis*) have been nearly extirpated as breeding populations.

At the same time, new land uses offer habitats for a different suite of species (Table 10-1). Humans have intentionally introduced the gray partridge (*Perdix*

Table 10-1. Examples of changes in species composition: increasing and decreasing species since European-American settlement.

Decreasing	Increasing
Idaho fescue/common snowberry association	Wheat
Festuca idahoensis/Symphoricarpos albus	*Triticum aestivum, T. compactum*
Idaho fescue/Nootka rose association	Barley
F. campestris/Rosa nutkana	*Hordeum vulgare*
Rough fescue/Idaho fescue association	Lentils
F. scabrella/F. idahoensis	*Lens* spp.
Smallheat goldenweed	Canola
Pyrrocoma liatriformis	*Brassica rapas*
Spalding's silene	Yellow star thistle
Silene spaldingii	*Centaurea solstitialis*
Jessica's aster	29 other noxious weeds
Aster jessicae	
Sharp-tailed grouse	Ring-necked pheasant
Pedioecetes phasianellus	*Phasianus colchicus*
Black-tailed jack rabbit	White-tailed jack rabbit
Lepus californicus	*L. townsendii*
Mule deer	White-tailed deer
Odocoileus hemionus	*O. virginianus*
Ferruginous hawk	European starling
Buteo regalis	*Sturnus vulgaris*
Spotted frog	Bullfrog
Rana pretiosa	*R. catesbeiana*

perdix), ringnecked pheasant (*Phasianus colchicus*), and chukar (*Alectoris chukar*), species which generally fare well in agricultural landscapes. Grazing, agriculture, and accidents have introduced a variety of exotic plants, many of which are vigorous enough to earn the title "noxious weed" (Table 10-2).

Conversion of agricultural lands to suburban homesites invites a second new suite of biodiversity onto the Palouse Prairie. A University of Idaho wildlife professor has documented changes in bird community composition over the past 10 years as he converted a wheat field into a suburban wildlife refuge. His 6-ha yard now attracts 86 species of birds, an increase from 18 (Ratti and Scott 1991). While many of the plant species he planted are nonnative, the majority of avian species using the habitat are native (95%).

Suburbanization of agricultural lands does not necessarily favor native species, however. Rural residents in Latah County have constructed some 1,500 ponds. These ponds are facilitating rapid colonization by an exotic bullfrog (*Rana catesbeiana*) which experts fear may compete with and/or eat native amphibians, including the sensitive spotted frog (*Rana pretiosa*; Monello and Wright 1997). The brown-headed cowbird (*Molothrus ater*) and European starling (*Sturnus vulgaris*) have taken advantage of the new habitats and moved into the area. The black-tailed jack rabbit (*Lepus californicus*) has largely displaced the white-tailed jack rabbit (Tisdale 1961; Johnson and Cassiday 1997).

Changes in biodiversity in the canyonlands follow a parallel track, though from slightly different causes. Due to steep slopes and infertile soils, the canyonlands have been used for grazing instead of farming (Tisdale 1986). Intense grazing and other disturbances have resulted in irreversible changes, with the native grasses being largely replaced by nonnative annual brome grasses and noxious weeds, particularly star thistles.

Change in Physical Resources

The Palouse region has one of the highest soil erosion rates in the country (U.S. Department of Agriculture 1978). Breaking of the original perennial grass cover left the soil vulnerable to erosion by wind and water. Commercial farming practices exacerbated these problems. Summer fallow leaves the soils with poor surface protection during the winter; burning straw and pea crop residues leave the soil with less organic binding material; and heavier, more powerful farming equipment pulverizes the soil, leaving it more vulnerable to wind and water erosion (Kaiser 1961).

Erosion measurements and control efforts began in the early 1930's. Soil loss by water erosion in the Palouse River basin from 1939 to 1972 was most severe in the heavily farmed areas of Whitman County, Washington, where soil losses of 15-18 tons per acre per year were mapped (U.S. Department of Agriculture 1978; Fig. 10-9). One major study reports that an average of 358 tons of soil was lost from every cropland acre in the basin from 1939 to 1972. This translates into an average of 0.2 tons of soil for every bushel

Table 10-2. Noxious weeds in Latah County, Idaho, and their origin (Callihan and Miller 1994).

Common Name	Scientific Name	Origin
Field bindweed	*Convolvulus arvensis*	Eurasia
Scotchbroom	*Cytisus scoparius*	Europe
Buffalobur nightshade	*Solanum rostratum*	Native to the Great Plains of the United States
Pepperweed whitetop	*Cardaria draba*	Europe
Common crupina	*Crupina vulgaris*	Eastern Mediterranean region
Jointed goatgrass	*Aegilops cylindrica*	Southern Europe and western Asia
Meadow hawkweed	*Hieracium caespitosum*	Europe
Orange hawkweed	*Hieracium aurantiacum*	Europe
Poison hemlock	*Conium maculatum*	Europe
Johnsongrass	*Sorghum halepense*	Mediterranean
White knapweed	*Centaurea diffusa*	Eurasia
Russian knapweed	*Acroptilon repens*	Southern Russia and Asia
Spotted knapweed	*Centaurea bibersteinii*	Europe
Purple loosestrife	*Lythrum salicaria*	Europe
Mat nardusgrass	*Nardus stricta*	Eastern Europe
Silverleaf nightshade	*Solanum elaeagnifolium*	Central United States
Puncturevine	*Tribulus terrestris*	Europe
Tansy ragwort	*Senecio jacobaea*	Eurasia
Rush skeletonweed	*Chondrilla juncea*	Eurasia
Wolf's milk	*Euphorbia esula*	Eurasia
Yellow star thistle	*Centaurea solstitialis*	Mediterranean and Asia
Canadian thistle	*Cirsium arvense*	Eurasia
Musk thistle	*Carduus nutans*	Eurasia
Scotch cottonthistle	*Onopordum acanthium*	Europe
Dalmatian toadflax	*Linaria dalmatica*	Mediterranean
Yellow toadflax	*Linaria vulgaris*	Europe

of wheat grown on the Palouse from 1939 to 1972 (U.S. Department of Agriculture 1978).

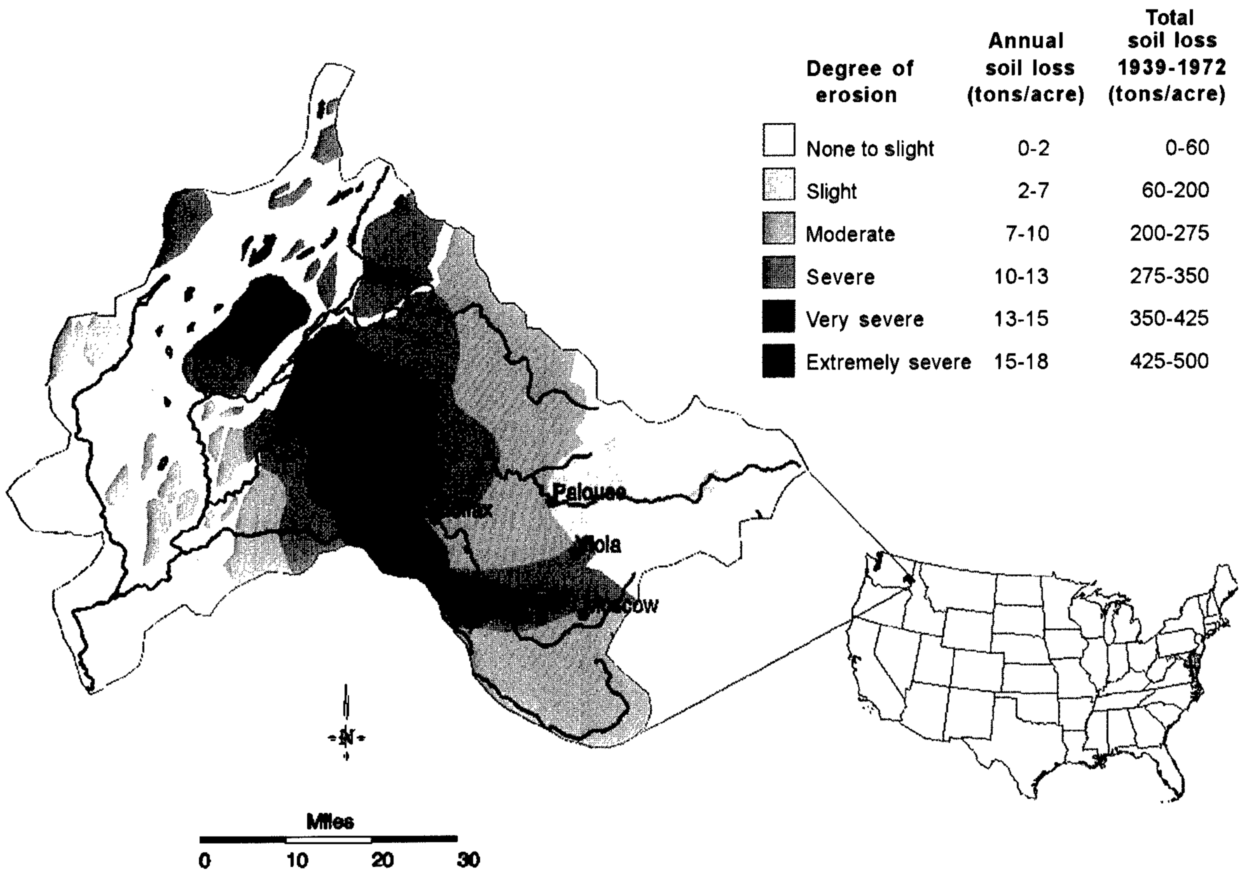
Intensification of agriculture has affected both water quantity and quality as well. Replacing perennial grasses with annual crops resulted in more overland flow and less infiltration, which translates at a watershed level to higher peak flows that subside more quickly than in the past. The result is more intense erosion and loss of perennial prairie streams. Once-perennial streams are now often dry by midsummer. As early as the 1930's soil scientists were noting significant downcutting of regional rivers (Victor 1935) due to higher, faster runoff, effectively lowering the water table in adjacent meadows. Nitrates from fertilizers have found their way into the surface aquifers as well. Nitrogen levels in groundwater have increased significantly (Jones and Wagner 1995; Wertz and Kinney 1995; U.S. Department of Agriculture 1995).

Change in Disturbance Regimes

Changes in vegetation and settlement pattern have changed the frequency, size, and pattern of the region's two major disturbances: fires and floods. While there is some debate over how frequently the Palouse Prairie burned historically, there is consensus that fires are generally less frequent today than in the past (Morgan et al. 1996). Historians recount lightning-ignited fires burning in the pine fringes bordering the prairies in late autumn, but the extent to which forest fires spread into the prairie or the converse is not known. In addition, some fire ecologists believe the Nez Perce burned the Palouse Prairie to encourage growth of camas (P. Morgan, University of Idaho, personal communication). Camas grows in seasonally wet areas and was harvested in the spring when it was easy to dig the bulbs from the damp soil; how camas responds to dry-season burning is unknown today.

European-American settlers used fire to clear land for settlement and grazing. Since then, forest fires have become less common because of fire suppression, human settlement, the presence of roads which act as fire breaks, and the conversion of grass and forests to cropland (Morgan et al. 1996). One result of the lower fire frequency has been increasing tree density on forested lands and encroachment of shrubs and trees into previously open areas. Consequently, when fires occur in forests they are more likely to result in mixed severity or stand-replacing events instead of the low severity fires of the past. Fires are still frequent in canyons, though today, fires give exotic annual grasses an edge over native species in burned areas.

Flooding on the major rivers has been curtailed in the region by large hydroelectric projects on the Snake and Clearwater Rivers. In addition to altering stream flow and channel scouring, the dams are major barriers to anadromous



fish. Changes in hydrology, such as drainage tiles placed under seasonally wet areas to allow agricultural production, removal of riparian vegetation, channeling of prairie streams, and building in flood plains, contribute to more severe localized flood events during winter and spring.

Conclusions

Conversion of the Palouse bioregion, particularly of the Palouse Prairie, from perennial native grass, shrub, and forest vegetation to agriculture has been so complete that it might seem a moot point to study its change. However, the processes by which the conversion occurred and the interactions between human cultures and environment influenced the extent and spatial pattern of landscape change, and therefore influenced wildlife population dynamics and viability. Linking these underlying processes to the resulting landscape patterns can provide new insight and make significant contributions to science and policy (Black et al. 1998). The conversion of more than 94% of the areas occupied by native landcover types makes the Palouse grasslands one of the most endangered ecosystems in the United States (Noss et al. 1995). Despite this loss of native habitats, no plant species (Lichthardt and Moseley 1996) or animal species (Buechner 1953; Tisdale 1986) have been lost from the Palouse. The earliest collections postdate extensive human use, however, so human impacts on native flora and fauna are probably greater than we were able to document. Several once common animal species, including ferruginous hawk, white-tailed jack rabbit, and sharp-tailed grouse, are rare and survive only as small relict populations in isolated fragments of habitat. Six globally rare plant species are endemic to the Palouse region (Lichthardt and Moseley 1996), and the integrity of remaining habitats for these and other species are low.

We used data from multiple spatial scales to analyze change. At the coarsest scale, native grasslands declined by more than 97% across the entire bioregion. However, certain critical habitat features, including remnant prairie vegetation, wet meadows, and shrubfields, were not adequately captured in the coarse resolution of the broad-scale data. Finer-scale ecological features and social system factors influencing conservation were examined in greater detail within the 875-ha study area. While this area was too small to allow extrapolation of results to the entire

bioregion, its small riparian patches and wetlands largely disappeared between 1940 and 1989, further reducing refugia and connectivity for native flora and fauna.

Projections of past vegetation based on soil characteristics documented in this century suggest that historical records may underestimate the total change from human influences. Yet, historical data are useful for evaluating changes in land cover and understanding the drivers of that change (Morgan et al. 1994). If collected over large areas, time-series data such as those compiled here offer an unprecedented opportunity to study species response to human land uses, including (1) the degree of change in habitat type and area, (2) the displacement of one suite of species with another as habitats change, and (3) the mechanisms, vectors, and rates of expansion and contraction of species. Further, understanding landscape changes provides critical information for outlining future research agendas, regulating development (Black et al. 1998), setting conservation goals, and targeting ecological restoration efforts.

The current suburbanization of the Palouse region provides opportunities for restoring native vegetation and enhancing animal species and populations (Ratti and Scott 1991). The loss of more than 98% of the native vegetation communities of the Palouse has not resulted in a single known species extinction or extirpation; however, the populations of six globally rare plant species endemic to the region (Lichthardt and Moseley 1996) have been reduced dramatically and survive only on isolated grassland remnants. These areas provide a logical starting point for efforts to restore native Palouse ecosystems.

Our analyses show that landscape changes are rarely gradual; they are episodic and at times the result of breakthroughs in agriculture technology. In the Palouse bioregion, episodes of change were based on breakthroughs associated with ever more intensive land uses. Railroads enabled agricultural settlement, engines and fertilizers commercialized farming and facilitated intensified land use, and now the information superhighway is enabling former city dwellers to relocate to rural areas (Rudzitis 1989). Each transition has been accompanied by changes in physical and biological conditions, including significant shifts in composition. At some point in time, if soil erosion is not curtailed, the physical capacity of this area to produce food will diminish; then we can expect a dramatic shift in both social and ecological systems. Whether these transitions are deemed favorable or not, time-series studies such as this provide new insights on regional change and offer critical information upon which to base land and resource management.

Acknowledgments

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Ecological change is constant and profound, yet often occurs at temporal and spatial scales that are difficult to measure and interpret. This publikcation demonstrates how diverse data bases, archived in different formats and at numerous locations, can be brought together to provide an integrated perspective on the relationship between land use and landcover change. The authors provide the historical context for interpreting recent landcover change in several regions of North America and articulate the value of a comprehensive, continental land use history for guiding environmental policy and management decisions during the coming century and beyond.

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